1

DESCRIPTION

MULTI-LAYER PIEZOELECTRIC ELEMENT

TECHNICAL FIELD

[0001]

The present invention relates to a multi-layer piezoelectric element and injection apparatus, for example, fuel injection apparatus of automobile engine, liquid injection apparatus of ink jet printer or the like or a drive unit used in precision positioning device or vibration preventing device for an optical apparatus, and to a multi-layer piezoelectric element used as a sensor element mounted in combustion pressure sensor, knocking sensor, acceleration sensor, load sensor, ultrasound sensor, pressure sensor, yaw rate sensor or the like, or used as a circuit component mounted in piezoelectric gyro, piezoelectric switch, piezoelectric transducer, piezoelectric breaker or the like.

BACKGROUND OF THE INVENTION

[0002]

Multi-layer piezoelectric actuators constituted from piezoelectric layers and electrodes stacked alternately one on another have been known as an example of the multi-layer piezoelectric element. The multi-layer piezoelectric actuators can be divided into two categories: fired-at-once type and stacked type which has such a constitution as piezoelectric porcelain and internal electrode sheets are

stacked one on another alternately. Due to the advantages of
lower operating voltage and lower manufacturing cost, the
multi-layer piezoelectric actuator of fired-at-once type has
been becoming dominant. The multi-layer piezoelectric

5   actuator of fired-at-once type is also more advantageous for
the reason of smaller layer thickness and higher durability.
[0003]

       Fig. 7 is a sectional view showing an example of the
multi-layer piezoelectric actuator of the prior art. This

10   multi-layer piezoelectric actuator comprises a stacked drive
section 53 formed by alternately stacking piezoelectric
layers 51 and internal electrodes 52 one on another, and
inactive protective sections 55 placed on both end faces of
the stack in the direction of stacking. The internal

15   electrodes 52 are formed so that an end of one of two
adjacent internal electrodes 52 is exposed on the side face
of the stacked drive section 53 and the other end is covered
by an insulating material 61. An external electrode 70 is
formed on the side face of the stacked drive section 53 where

20   the end of the internal electrode 52 is exposed, while the
other internal electrode 52 of which end is not covered by
the insulating material 61 is connected to the external
electrode 70.
[0004]

25   Fig. 8 is a sectional view showing another example of

the multi-layer piezoelectric element of the prior art. In

this example, while piezoelectric layers 51 and the internal

electrodes 52 are stacked alternately one on another, the

internal electrode 52a is not formed over the entire

5   principal surface of the piezoelectric layer 51, but is

formed in a so-called partial electrode structure. The

internal electrodes 52 having the partial electrode structure

are stacked in a staggered manner, so that the internal

electrodes 52 are connected to the external electrodes 54,

10   which are formed on the side faces of the multi-layer

electronic component, alternately in every other layer. In

case the multi-layer piezoelectric element is used as a

multi-layer piezoelectric actuator, lead wires (not shown)

are soldered onto the external electrodes 54.

15   [0005]

The multi-layer piezoelectric element shown in Fig. 8 is

also constituted from the stacked drive section 63 formed by

alternately stacking the piezoelectric layers 51 and the

internal electrodes 52 one on another, and inactive

20   protective sections 62 provided on the upper end and on the

lower end of the stack in the direction of stacking. The

inactive protective sections 62 ordinarily do not include

electrode layer, although electrode layer similar to the

stacked drive section 63 is stacked on the inactive

25   protective sections 62 in order to prevent stress from being

generated and cracks from occurring after sintering due to difference in the shrinkage between the stacked drive section 63 and the inactive protective sections 62 (refer, for example, to Patent Document 4).

5 [0006]

The multi-layer piezoelectric element is manufactured by printing a paste used to form the internal electrode in a predetermined pattern on ceramic green sheets that would become the piezoelectric layers, stacking a plurality of the

10 green sheets having the paste for the internal electrode printed thereon, firing the stack and baking an electrically conductive paste that would become the external electrode on the side faces (refer, for example, to Patent Document 1). [0007]

15 The internal electrode 52 is formed from an alloy of silver and palladium and, in order to fire the piezoelectric material 51 and the internal electrodes 52 at the same time, the composition of metals contained in the internal electrode 52 is set to 70% by weight of silver and 30% by weight of

20 palladium (refer to, for example, Patent Document 2).

However, there have been such problems that the internal electrodes made of a metal have weak strength of adhesion with the piezoelectric material, while internal stress generated by the difference in thermal expansion of both

25 members causes cracks in the interface between the internal

electrode and the piezoelectric layer and, in the worst case,
the stack would break. In order to eliminate such problems,
for example, Patent Document 3 describes a method of
increasing the strength of adhesion between the piezoelectric
5   layer and the internal electrode by mixing a ceramic powder
in the internal electrode.
[0008]

In recent years, it has been in practice to carry out
continuous operation of piezoelectric actuators over a long
10   period of time with a higher electric field applied, in order
to achieve a large amount of displacement with a compact
piezoelectric actuator under a high pressure.
Patent Document 1: Japanese Unexamined Patent Publication
(Kokai) No. 61-133715
15   Patent Document 2: Japanese Unexamined Utility Model
Publication (Kokai) No. 1-130568
Patent Document 3: Japanese Unexamined Patent Publication
(Kokai) No. 4-299588
Patent Document 4: Japanese Unexamined Patent Publication
20   (Kokai) No. 9-270540
DISCLOSURE OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

[0009]

There has been such a problem that the amount of
25   displacement of a piezoelectric material varies as the

ambient temperature becomes higher, and therefore when the
device temperature becomes higher, thus the amount of
displacement of a piezoelectric actuator changes. A change
in the amount of displacement during operation of the

5   actuator causes fluctuation in the load on the power source
that supplies the voltage, thus placing a burden on the power
source. When the amount of displacement undergoes a rapid
change, not only the amount of displacement deteriorates
rapidly but also the heat generated by the device exceeds the

10   heat that can be removed by dissipation and thermal excursion
occurs, thus resulting in breakage and failure.
[0010]

It is effective to use an internal electrode that has
lower specific resistance, in order to keep the device

15   temperature from rising. However, the silver-palladium alloy
has a specific resistance higher than that of pure silver or
pure palladium, and the silver-palladium alloy having
composition of 70% by weight of silver and 30% by weight of
palladium shows a specific resistance 1.5 times that of pure

20   palladium. In addition, resistance of an internal electrode
made by sintering with a lower density becomes even higher.

In the multi-layer piezoelectric actuator of the prior
art, there has been such a problem that the internal
electrode that is softer than the piezoelectric material

25   absorbs a part of the displacement of the piezoelectric

material, thus causing the amount of displacement to vary. There has also been such a problem related to durability that the variation in the amount of displacement increases after repeated operations over a long period of time. These

5   problems cannot be solved by the method described in Patent Document 3 of increasing the strength of adhesion between the piezoelectric material 51 and the internal electrode 52 by mixing a ceramic powder in the internal electrode 52.
[0011]

10   In the recent practice of carrying out continuous operation over a long period of time with a higher electric field applied, in order to cause a compact piezoelectric actuator to achieve a large amount of displacement under a high pressure, there are such problems as the amount of

15   displacement varies among the individual actuators in the early stage of use. The amount of displacement also changes with time over a long period of operation.
[0012]

Furthermore, operation of the multi-layer piezoelectric

20   actuator is based on the deformation of porcelain of the piezoelectric material under a voltage, unlike the conventional multi-layer electronic component (for example, multi-layer ceramic capacitor). That is, the porcelain of the piezoelectric material deforms the same number of times

25   as the number of operation cycles. In recent years, it is

required to carry out continuous operation over a long period of time with a higher electric field applied, in order to make a compact piezoelectric actuator capable of achieving a large amount of displacement under a high pressure.

5   [0013]

However, the improvement described in Patent Document 4 has such a problem that continuous operation over a long period of time with a higher electric field applied thereto leads to the occurrence of cracks that disables the actuator

10   to function, thus indicating a drawback with regards to durability.

An object of the present invention is to provide a multi-layer piezoelectric element of high reliability and high durability, that undergoes smaller variations in the

15   amount of displacement even when used under a high electric field and high pressure and is subject to less variations in the amount of displacement even when used in continuous operation over a long period of time, and an injection apparatus.

20   MEANS FOR SOLVING THE PROBLEMS

[0014]

First multi-layer piezoelectric element of the present invention, aimed at achieving the object described above, comprises a stack formed by stacking piezoelectric layers and

25   internal electrodes alternately one on another and external

electrodes formed on a first side face and on a second side face of the stack, wherein one of the adjacent internal electrodes is connected to the external electrode on the first side face and the other internal electrode is connected

5   to the external electrode formed on the second side face, while the ratio of change in the amount of displacement of the element after undergoing continuous operation of 1×10^9 cycles or more to the initial device dimension is not larger than 5%.

10   The first multi-layer piezoelectric element of the present invention that is constituted as described above does not cause malfunction of the apparatus and has excellent durability free of thermal excursion, since the amount of displacement does not substantially change after continuous

15   operation.

[0015]

Second multi-layer piezoelectric element of the present invention comprises a stack formed by stacking piezoelectric layers and internal electrodes alternately one on another and

20   external electrodes formed on a first side face and on a second side face of the stack, wherein one of the adjacent internal electrodes is connected to the external electrode on the first side face and the other internal electrode is connected to the external electrode formed on the second side

25   face, while the ratio of change in the resistance of the

element after undergoing continuous operation of 1×10^9 cycles or more to the initial value of resistance is not larger than 5%.

The second multi-layer piezoelectric element of the present invention constituted as described above does not cause malfunction of the apparatus and has excellent durability free of thermal excursion, as the change in resistance of the element is controlled to 5% or less.

[0016]

In the first and second multi-layer piezoelectric elements of the present invention, maximum change in the amount of displacement of the element during continuous operation is preferably not larger than 5%, which enables it to prevent malfunction of the apparatus more effectively and provide excellent durability free of thermal excursion.

[0017]

In the first and second multi-layer piezoelectric elements of the present invention, the ratio of change in thickness of the piezoelectric layer after undergoing continuous operation of 1×10^9 cycles or more to the thickness of the piezoelectric layer before the continuous operation is preferably not larger than 5%,.

By restricting change the in thickness of the piezoelectric layer after operation to within 5%, it is made possible to prevent malfunction of the apparatus more

effectively and provide excellent durability free of thermal excursion.

[0018]

In the first and second multi-layer piezoelectric elements of the present invention, maximum change in resistance of the element during continuous operation is preferably not larger than 5%.

By restricting the change in resistance of the piezoelectric layer during continuous operation to within 5%, it is made possible to prevent malfunction of the apparatus effectively and provide excellent durability free of thermal excursion.

[0019]

Third multi-layer piezoelectric element of the present invention comprises a stack formed by stacking piezoelectric layers and internal electrodes alternately one on another and external electrodes formed on a first side face and on a second side face of the stack, wherein one of the adjacent internal electrodes is connected to the external electrode on the first side face and the other internal electrode is connected to the external electrode formed on the second side face, while pillars are provided to penetrate the internal electrode and connect the piezoelectric layers that oppose each other via the internal electrode.

[0020]

The third multi-layer piezoelectric element of the present invention constituted as described above can minimize the variation in the amount of displacement by providing the pillars that connect the piezoelectric layers in the internal electrode. Also it is made possible to provide the piezoelectric actuator that has high reliability and improved durability and undergoes less variation in the amount of displacement after continuous operation over a long period of time. As a result, for example, an injection apparatus that is excellent in durability and has high reliability can be provided.

[0021]

In the third multi-layer piezoelectric element of the present invention, it is preferable that not less than 30% of the pillars have diameter in the section thereof joined with the piezoelectric layer not smaller than 50% of the maximum diameter of the pillars.

[0022]

In the third multi-layer piezoelectric element of the present invention, it is also preferable that mean value of minimum diameters of the pillars is not smaller than 0.2 μm.

[0023]

In the third multi-layer piezoelectric element of the present invention, it is further preferable that the number of pillars per 1 mm is from 5 to 150.

[0024]

In the third multi-layer piezoelectric element of the present invention, it is further preferable that the difference in thermal expansion coefficient between the pillar and the piezoelectric material that constitutes the piezoelectric layers is $3 \times 10^{-5}/°C$ or less.

[0025]

In the third multi-layer piezoelectric element of the present invention, it is also preferable that the pillars are formed from the same material as that of the piezoelectric material.

[0026]

In the first through third multi-layer piezoelectric elements of the present invention that are constituted as described above, it is preferable that the stack includes inactive protective layers formed by alternately stacking the piezoelectric layers and dummy layers on the top and bottom thereof, and the ratio A/B of minimum distance A between the periphery of the dummy layer and the side face of the inactive protective layers to width B of the inactive protective layer is in a range from 0.01 to 0.08.

The minimum distance A is the length of the protective section along a plane cutting the protective section in the direction perpendicular to the direction of stacking, and width B of the inactive protective section is the length in

the same direction as the minimum distance A is measured.

[0027]

   With the multi-layer piezoelectric element constituted as described above, it is made possible to achieve uniform shrinkage during firing and, as a proper region of junction is provided between the piezoelectric layers, stress generated between the inactive protective section and the stacked drive section can be mitigated. As a result, durability can be improved even when operated continuously under a high voltage over a long period of time, and an injection apparatus comprising the multi-layer piezoelectric element having excellent durability can be provided.

[0028]

   The inventor of the present application conducted a research into the minimum distance between the periphery of the dummy layer and the side face of the inactive protective layers and durability, and found a relationship between the minimum distance and durability. That is, it was found that durability can be greatly improved by controlling the minimum distance between the periphery of the dummy layer and the side face of the inactive protective layers.

[0029]

   In the multi-layer piezoelectric elements of the present invention that has the dummy layer, it is preferable that the dummy layer contains a metal.

[0030]

It is also preferable that the dummy layer is formed from the same material as that of the internal electrode.

It is also preferable that the dummy layer contains an inorganic composition, that is a metal oxide, nitride or carbide, and that the dummy layer contains 2% by weight or more of an inorganic composition.

[0031]

The piezoelectric layer has thickness preferably not less than 50 µm.

[0032]

In the first through third multi-layer piezoelectric elements of the present invention that are constituted as described above, it is preferable that the metal composition in the internal electrode contains group VIII metal and/or group Ib metal as the main component.

When the metal composition in the internal electrode contains group VIII metal and/or group Ib metal as the main components, the internal electrode can be formed from the metal composition that has high heat resistance and therefore can be fired together with the piezoelectric material that has a higher firing temperature at the same time.

[0033]

In the first through third multi-layer piezoelectric elements of the present invention wherein the internal

electrode contains group VIII metal and/or group Ib metal as the main components, it is preferable that proportion M1 (% by weight) of the group VIII metal and proportion M2 (% by weight) of the group Ib metal in the internal electrode

5   satisfy the relations $0 < M1 \leq 15$, $85 \leq M2 < 100$ and M1 + M2 = 100, so that specific resistance of the internal electrode can be kept low. As a result, generation of heat from the internal electrode can be suppressed even when the multi-layer piezoelectric element is operated continuously over a

10   long period of time. Moreover, since the temperature of the multi-layer piezoelectric element can be suppressed from increasing, the amount of displacement of the device can be stabilized.

[0034]

15   In the multi-layer piezoelectric element of the present invention, it is preferable that the group VIII metal is at least one kind selected from among Ni, Pt, Pd, Rh, Ir, Ru and Os, and the group Ib metal is at least one kind selected from among Cu, Ag and Au. Either alloy materials or mixed powder

20   materials may be used to form the internal electrode, as long as they are selected from those listed above.

[0035]

Further, when the group VIII metal is at least one kind selected from among Pt and Pd, and the group Ib metal is at

25   least one kind selected from among Ag and Au, the internal

electrode having high heat resistance and high oxidation
resistance can be formed.

[0036]

    Further, when the group VIII metal is Ni, stress
5   generated by the displacement during operation can be
mitigated and the internal electrode that is excellent in
heat resistance can be formed.

[0037]

    When the group Ib metal is Cu, stress generated by the
10   displacement during operation can be mitigated and the
internal electrode that is excellent in heat conductivity can
be formed.

[0038]

    Moreover, adhesive strength in the interface between the
15   internal electrode and the piezoelectric material can be
increased by adding oxide, nitride or carbide along with the
metal composition to the internal electrode, thus suppressing
peel-off from occurring in the interface between the internal
electrode and the piezoelectric material.

20   It is preferable that the oxide described above contains
perovskite type oxide consisting of $PbZrO_3$-$PbTiO_3$ as the main
component.

[0039]

    It is further preferable that the piezoelectric layers
25   contain perovskite type oxide as the main component.

[0040]

By forming the piezoelectric material from the perovskite type oxide consisting of $PbZrO_3$-$PbTiO_3$ as the main component, it is made possible to fire the internal electrode and the piezoelectric material at the same time, thereby reducing the time required in the firing process while achieving lower specific resistance of the internal electrode.

[0041]

Firing temperature of the stack is preferably in a range from 900 to 1000°C.

[0042]

By controlling the deviation in the composition of the internal electrode that is caused by the firing operation within 5%, the internal electrode is enabled to deform in conformity with the expansion and contraction of the multi-layer piezoelectric element during the operation, thus making it possible to suppress the internal electrode from coming off.

[0043]

In the first through third multi-layer piezoelectric elements of the present invention, it is further preferable that the internal electrode of which end is exposed on the side face of the stack and the internal electrode of which end is not exposed are stacked alternately, while a groove is formed in the piezoelectric layer located between the

internal electrode of which end is not exposed and the external electrode, with the groove being filled with an insulating material that has a value of Young's modulus lower than that of the piezoelectric layer.

5   [0044]

In the first through third multi-layer piezoelectric elements of the present invention, it is also preferable that the internal electrode includes voids and the voids occupy 5 to 70% of cross sectional area of the internal electrode.

10   This constitution decreases the restrictive force exerted by the internal electrode on the deformation of the piezoelectric material under the effect of electric field, thereby increasing the amount of displacement of the piezoelectric material. It also provides such an advantage

15   that stress generated in the internal electrode is mitigated by the voids, thereby improving the durability of the element. In addition, while heat transfer within the element is predominantly carried by the internal electrode, existence of the voids in the internal electrode mitigates the change in

20   temperature within the element caused by rapid changes in the temperature outside of the element, thus making the element more resistant to thermal shock.

[0045]

The injection apparatus of the present invention

25   comprises a container having an injection hole, one of the

first through third multi-layer piezoelectric elements housed in the container and a valve that allows a liquid to be ejected by the multi-layer piezoelectric element through the injection hole.

5   This constitution provides an injection apparatus that has high durability.

BRIEF DESCRIPTION OF THE DRAWINGS

[0046]

Fig. 1A is a perspective view showing the multi-layer
10   piezoelectric element of the present invention.

Fig. 1B is an exploded perspective view showing the piezoelectric layers and the internal electrodes being stacked in the multi-layer piezoelectric element of the present invention.

15   Fig. 2A is a perspective view showing the multi-layer piezoelectric element according to the second embodiment of the present invention.

Fig. 2B is a side view of the multi-layer piezoelectric element according to the second embodiment.

20   Fig. 3 is an enlarged sectional view of a part of the multi-layer piezoelectric element according to the second embodiment.

Fig. 4A is a perspective view showing a multi-layer piezoelectric element having an electrical conductivity
25   assisting member formed on the outer surface of the external

electrode.

Fig. 4B is a sectional view showing the multi-layer piezoelectric element having the electrical conductivity assisting member formed on the outer surface of the external electrode.

Fig. 5A is a perspective view showing the multi-layer piezoelectric element according to the third embodiment of the present invention.

Fig. 5B is a sectional view showing the piezoelectric layers, the internal electrodes, protective section and dummy layers being stacked in the multi-layer piezoelectric element of the third embodiment.

Fig. 6 is a side view showing the injection apparatus of the present invention.

Fig. 7 is a side view showing the multi-layer piezoelectric actuator of the prior art.

Fig. 8 is a sectional view showing a part of the multi-layer piezoelectric element of the prior art.

[Description of Reference Numerals]

[0047]

1:    Piezoelectric material

2:    Internal electrode

3:    Insulating material

4:    External electrode

13:   Stacked drive section

14, 20:   Inactive protective section

18: Pillar

21: Dummy layer

22: Junction between pillar and piezoelectric material

5   31: Container

33: Injection hole

35: Needle valve

37: Fuel passage

39: Cylinder

10   41: Piston

43: Piezoelectric actuator

BEST MODE FOR CARRYING OUT THE INVENTION

[0048]

embodiments of the present invention will now be

15   described below with reference to the accompanying drawings.

First Embodiment

Fig. 1A is a perspective view of the multi-layer

piezoelectric element according to the first embodiment of

the present invention, and Fig. 1B is an exploded perspective

20   view showing the piezoelectric layers 1 and the internal

electrodes 2 being stacked one on another.

The multi-layer piezoelectric actuator of the first

embodiment comprises a stack having rectangular prism shape

formed by stacking a plurality of piezoelectric layers 1 and

25   a plurality of internal electrodes 2 alternately, and

external electrodes 4 formed on the side faces of the stack

so as to be connected to the internal electrodes 2 in every

other layer, as shown in Fig. 1A and Fig. 1B.

[0049]

5   Specifically, an end of the internal electrode 2 is

exposed on the side face whereon the external electrode 4 is

formed in every other layer, so that the end of the internal

electrode 2 that is exposed is electrically connected to the

external electrode 4. The portion of the stack indicated

10   with reference numeral 14 is the inactive protective section

formed by stacking the piezoelectric layer 1 without internal

electrodes 2 included therein. When the multi-layer

piezoelectric element of the first embodiment is used as a

multi-layer piezoelectric actuator, lead wires may be

15   connected to the external electrodes 4 by soldering, with the

lead wires being connected to a power source installed

outside.

[0050]

While the internal electrode 2 is disposed between the

20   piezoelectric layers 1, the internal electrode 2 is used to

apply a predetermined voltage to the piezoelectric layers 1,

so that the piezoelectric element 1 undergoes a displacement

by the reverse piezoelectric effect, and is formed from a

metallic material such as silver-palladium.

25   [0051]

The inactive protective section 14 is constituted from a plurality of piezoelectric layers 1 without the internal electrodes 2 provided. The inactive protective section 14 does not make displacement when a voltage is applied thereto.

5 [0052]

The multi-layer piezoelectric element of the first embodiment is constituted so that the change in displacement of the element after operation is within 5% even when operated repetitively. That is, the multi-layer

10 piezoelectric element of the first embodiment has very high durability as the change in displacement of the element after continuous operation is kept within 5%.

[0053]

The ratio of change in displacement of the element after

15 continuous operation refers to the ratio of change in displacement of the multi-layer piezoelectric element after repetitive operations to the amount of displacement before being put into continuous operation.

[0054]

20 Specifically, after the multi-layer piezoelectric element has been made, DC voltage of a predetermined magnitude is applied to the multi-layer piezoelectric element and the amount of displacement (initial displacement) is determined before putting the multi-layer piezoelectric

25 element into continuous operation.

Then an arbitrary AC voltage is applied to the multi-layer piezoelectric element and, after driving it to undergo about 1×10^9 cycles of operation consecutively, DC voltage of the same magnitude as that used when measuring the initial

5 displacement is applied and the amount of displacement is determined (amount of displacement after continuous operation).

Then the ratio of the change in the amount of displacement after continuous operation to the amount of

10 initial displacement is taken as the ratio of the change in the displacement of the element after continuous operation.
[0055]

The ratio of change in the displacement of the element after continuous operation is given by the formula:

15 {100 × (Displacement after continuous operation – Initial displacement)/(Initial displacement)}

Further the multi-layer piezoelectric element of the first embodiment is constituted so that maximum ratio of change in the displacement of the element during continuous

20 operation is not larger than 5%. This is because the maximum ratio of change in the displacement of the multi-layer piezoelectric element exceeding 5% during continuous operation may cause deterioration of the multi-layer piezoelectric element during operation, thus resulting in

25 lower durability of the multi-layer piezoelectric element.

[0056]

The maximum ratio of change in the displacement of the element during continuous operation is determined as follows. The amount of displacement before continuous operation (amount of displacement in the initial state) is determined by applying a DC voltage to the multi-layer piezoelectric element. Then an AC voltage of the same magnitude as the DC voltage used when measuring the initial displacement is applied to the multi-layer piezoelectric element and the displacement is measured in every cycle during about 1×10^8 cycles of operation. The largest displacement among the measured values is taken as the maximum displacement, and the ratio of the maximum displacement to the amount of displacement before the continuous operation is determined.

[0057]

While continuous operation under application of an AC voltage has been described, continuous operation may also be carried out under a pulse voltage in which case, too, the multi-layer piezoelectric element is constituted such that the maximum ratio of change in the amount of displacement during continuous operation is within 5%. For example, the amount of displacement of the multi-layer piezoelectric element under a DC voltage of 150 V is taken as the amount of displacement in the initial state. Then pulse voltage of 0 V and 150 V is applied to have the multi-layer piezoelectric

element undergo about 1×10^8 cycles of continuous operation while measuring the displacement in each cycle. The element of the present invention is constituted so that the largest displacement during this continuous operation is within 5%.

5   [0058]

The DC voltage, AC voltage and pulse voltage used when measuring the initial displacement may be set freely in a range from 100 V to 200 V.

The multi-layer piezoelectric element of the present invention is constituted such that ratio of change in thickness of the piezoelectric layer after continuous operation is not larger than 5%. This is because, when the ratio of change in thickness of the piezoelectric layer after continuous operation is larger than 5%, dimension of the multi-layer piezoelectric element itself changes, resulting in change in the amount of displacement. This accelerates the deterioration of the multi-layer piezoelectric element and results in significant decrease in durability of the multi-layer piezoelectric element.

20   [0059]

Thickness of the piezoelectric layer can be measured by observing the piezoelectric layer in a section or side face of the multi-layer piezoelectric element under an SEM.

The ratio of change in thickness of the piezoelectric layer after operation refers to the ratio of change in

thickness of the piezoelectric layer in the stacking direction, after about 1×10^9 cycles of continuous operation under an AC voltage applied to the multi-layer piezoelectric element, to the thickness of the piezoelectric layer before

5   the continuous operation.

[0060]

The ratio of change in thickness of the piezoelectric layer can be determined by observing the side face of the multi-layer piezoelectric element under an SEM before

10   operation to measure the thickness of the piezoelectric layer at 10 points and average the measurements, while measuring the thickness of the piezoelectric layer after the continuous operation at the same points and averaging the measurements.

[0061]

15   The multi-layer piezoelectric element of the first embodiment is constituted such that ratio of change in resistance of the multi-layer piezoelectric element after continuous operation is not larger than 5%. This is because, when the ratio of change in resistance of the multi-layer

20   piezoelectric element after continuous operation exceeds 5%, the multi-layer piezoelectric element is subjected to more significant deterioration resulting in significantly lower durability of the multi-layer piezoelectric element.

[0062]

25   The ratio of change in resistance of the multi-layer

piezoelectric element after continuous operation is

determined as follows. Resistance of the element before

continuous operation is measured by applying a DC voltage to

the multi-layer piezoelectric element. Then an AC voltage is

5   applied to the multi-layer piezoelectric element and

resistance of the element is measured after about 1×10^9

cycles of continuous operation. The ratio of the resistance

of the element after the continuous operation to the

resistance of the element before the continuous operation is

10   taken as the ratio of change in resistance.

[0063]

Further the multi-layer piezoelectric element of the

first embodiment is constituted so that maximum change in

resistance of the element during continuous operation is not

15   larger than 5%. This is because maximum change in the

resistance of the multi-layer piezoelectric element exceeding

5% during continuous operation may cause deterioration of the

multi-layer piezoelectric element during operation, thus

resulting in lower durability of the multi-layer

20   piezoelectric element.

[0064]

The maximum change in resistance of the multi-layer

piezoelectric element after continuous operation is

determined as follows. Resistance of the element before

25   continuous operation is measured by applying a DC voltage to

the multi-layer piezoelectric element. Then an AC voltage is applied to the multi-layer piezoelectric element and maximum resistance of the element measured during continuous operation of about 1×10^8 cycles is taken as the resistance

5   of the element during continuous operation. The ratio of the resistance during the continuous operation to the resistance of the element before the continuous operation is taken as the maximum change in resistance.

[0065]

10   In the multi-layer piezoelectric element of the present invention constituted as described above, the amounts of displacement of the element after continuous operation and during continuous operation, change in thickness of the piezoelectric layer after continuous operation, and changes

15   in resistance of the element after continuous operation and during continuous operation can be controlled within 5% as follows.

[0066]

For the purpose of restricting the amounts of

20   displacement of the element, change in thickness of the piezoelectric layer and change in resistance of the element, such methods have been employed as maintaining the element temperature constant during continuous operation or minutely controlling the operating voltage in accordance to the

25   element temperature. Specifically, the operating voltage is

controlled while monitoring the element temperature, or

temperature around the element is controlled by means of a

heat sink installed so as to dissipate heat.

[0067]

5   According to the first embodiment of the present

invention, in contrast, the element temperature is controlled

(device temperature is suppressed from changing) during

continuous operation by suppressing the heat from being

generated by the operation of the element. In order to

10   control the device temperature during operation (to suppress

device temperature from changing), it is necessary to

decrease the induction loss (tan δ) of the piezoelectric

material 1 and/or decrease device resistance.

[0068]

15   Since thickness of the piezoelectric layer changes

depending on the degree of polarization, it is necessary to

decrease the induction loss (tan δ) of the piezoelectric

material so that the state of polarization after continuous

operation remains the same as that before the continuous

20   operation, in order to maintain the change in thickness of

the piezoelectric layer constant after continuous operation.

When temperature of the piezoelectric layer becomes higher

than Curie point, the state of polarization during continuous

operation becomes different from the state of polarization

25   before continuous operation, thus making thickness and the

amount of displacement of the piezoelectric layer more prone

to change after continuous operation. Therefore, it is

necessary to suppress the device temperature from rising.

Thus it is required to decrease the specific resistance of

5   the electrode material thereby to suppress the device

temperature from rising during operation.

[0069]

In case the piezoelectric layer 1 is formed by using

perovskite type oxide consisting of $PbZrO_3-PbTiO_3$ as the main

10   component, induction loss (tan δ) may be decreased by firing

the stack in oxygen-rich atmosphere, or by lowering the

temperature more slowly from the highest firing temperature

after firing the stack. Specifically, temperature lowering

rate may be 600°C per hour or less, preferably 300°C per hour

15   or less. Induction loss (tan δ) may be below 1.5%,

preferably 0.5% or lower.

[0070]

Resistance of the device may be decreased by using a

material of such a composition that has lower specific

20   resistance to form the internal electrodes 2 and forming a

dense structure that provides a sufficient path for current.

Moreover, since the amount of displacement of the

material that forms the piezoelectric layer 1 is desired to

be independent of the operating temperature and remains

25   constant, it is preferable to use a piezoelectric material

that undergoes smaller displacement over the range of
temperatures experienced by the element during continuous
operation.

Furthermore, in order to remove the heat generated by
the device efficiently to the outside, it is preferable to
form the internal electrodes 2 that serve as the major path
of heat transmission from a material that has high heat
conductivity.

[0071]

A method of manufacturing the multi-layer piezoelectric
element of the first embodiment will now be described below.

First, a calcined powder of a piezoelectric ceramic
material constituted from perovskite type oxide consisting of
$PbZrO_3$-$PbTiO_3$ or the like, a binder made of an organic
polymer such as acrylic resin or butyral resin and a
plasticizer such as DOP (dioctyl phthalate) or DBP (dibutyl
phthalate) are mixed to form a slurry. The slurry is formed
into ceramic green sheets that would become the piezoelectric
layers 1 by a known method such as doctor blade process or
calender roll process or other tape molding method.

[0072]

Then a metal powder such as silver-palladium that
constitutes the internal electrode, a binder and a
plasticizer are mixed to prepare an electrically conductive
paste which is applied onto the top surface of the ceramic

green sheet by screen printing method or the like to a thickness of 1 to 40 µm.

A plurality of the green sheets having the electrically conductive paste printed on the top surface thereof are stacked one on another, with the stack being heated at a predetermined temperature to remove the binder. The stack is then fired at a temperature in a range from 900 to 1200°C thereby to make the stack.

[0073]

The method of making the stack is not limited to that described above, and any manufacturing method may be employed as long as the stack can be made in such a constitution as a plurality of the piezoelectric layers 1 and a plurality of the internal electrodes 2 are stacked alternately one on another.

[0074]

The stack is made so that an end of the internal electrode is exposed on the side face of the stack in every other layer. A groove may be formed in the piezoelectric material located between the internal electrode 2 of which end is not exposed and the external electrode 4, with the groove filled with an insulating material such as resin or rubber that has Young's modulus lower than that of the piezoelectric material 1. The groove is formed on the side face of the stack by means of a dicing apparatus or the like.

[0075]

Then an electrically conductive silver-glass paste is prepared by adding a binder to a glass powder, and the mixture is formed into a sheet that is dried to remove solvent while controlling the density of the green sheet in a range from 6 to 9 g/cm^3. The sheet is transferred onto the external electrode forming surface of the column-like stack, and is bonded by baking at a temperature that is higher than the softening point of the glass and is not higher than the melting point (965°C) of silver and is not higher than 4/5 of the firing temperature (°C). In this process, the binder contained in the sheet that is formed from the electrically conductive silver-glass paste is evaporated and removed, so that the external electrode 4 is formed from a porous electrical conductor having 3-dimensional mesh structure.

The electrically conductive material that constitutes the external electrode 4 is preferably silver that has a low value of Young's modulus or an alloy based on silver, in consideration of the capability to sufficiently absorb the stress generated by the expansion and contraction of the actuator.

[0076]

The temperature at which the electrically conductive silver-glass paste is bonded by baking is preferably in a range from 550 to 700°C for the purpose of joining the silver

content that is included in the electrically conductive

silver-glass paste and the internal electrode 2 through

diffusion bonding so as to form an effective neck,

effectively causing the voids existing in the external

5   electrode 4 to remain and partially joining the external

electrode 4 and the side face of the column-like stack.

Softening point of the glass component contained in the

electrically conductive silver-glass paste is preferably in a

range from 500 to 700°C.

10   [0077]

When the baking temperature is higher than 700°C,

sintering of the silver powder of the electrically conductive

silver-glass paste would proceed excessively, such that the

porous electrical conductor of 3-dimensional mesh structure

15   cannot be effectively formed and the external electrodes 4

become too dense. As a result, the value of Young's modulus

of the external electrode 4 becomes too high to effectively

absorb the stress generated during operation, eventually

leading to breakage of the external electrode 4. Baking is

20   preferably carried out at a temperature that is not higher

than 1.2 times the softening point of the glass.

[0078]

When the baking temperature is lower than 550°C, on the

other hand, the end of the internal electrode 2 and the

25   external electrode 4 cannot be joined sufficiently through

diffusion bonding, and therefore the neck cannot be formed thus giving rise to the possibility of spark occurring between the internal electrode 2 and the external electrode 4 during operation.

5   Thickness of the sheet formed from the electrically conductive silver-glass paste is preferably smaller than the thickness of the piezoelectric layer 1. More preferably, the thickness is 50 μm or less in order to accommodate the contraction and expansion of the actuator. By forming the

10   external electrode 4 as described above, the multi-layer piezoelectric element of the first embodiment is completed.
[0079]

Then the stack having the groove formed on the side face thereof to reach the inner electrode and the external

15   electrodes 4 formed thereon is immersed in a silicone rubber solution while deaerating the silicone rubber solution by evacuation, so as to fill the groove of the stack with the silicone rubber. Then the stack is pulled out of the silicone rubber solution and is coated with the silicone

20   rubber on the side faces thereof. Then the silicon rubber that fills the groove and covers the side faces of the column-like stack is cured, thereby to complete the multi-layer piezoelectric element of the present invention.
[0080]

25   Then lead wires are connected to the external electrodes

4, and DC voltage of 0.1 to 3 kV/mm is applied between the pair of external electrodes 4 via the lead wires so as to apply polarization treatment to the stack, thereby to complete the multi-layer piezoelectric actuator that utilizes

5   the multi-layer piezoelectric element of the present invention. When the lead wires are connected to an external voltage source and the voltage is supplied via the lead wires and the external electrodes 4 to the internal electrodes 2, the piezoelectric layers 1 undergo a significant amount of

10   displacement by the reverse piezoelectric effect. The multi-layer piezoelectric actuator of the first embodiment constituted as described above can be used, for example, as an automobile fuel injection valve that supplies fuel to an engine.

15   [0081]

Second Embodiment

       Fig. 2A is a perspective view showing the constitution of the multi-layer piezoelectric actuator according to the second embodiment of the present invention, and Fig. 2B is a

20   side view thereof. Fig. 3 is a sectional view of a part of the internal electrode 2.

[0082]

       The multi-layer piezoelectric actuator according to the second embodiment has such a constitution as the external

25   electrodes 4 are provided on the side faces of a stack 10

having rectangular prism shape formed by alternately stacking the piezoelectric layers 1 and the internal electrodes 2 as shown in Figs. 2A and 2B, so that one end of the internal electrode 2 is covered by an insulating material 3 in every

5   other layer and the external electrode 4 is connected to the end of the internal electrode 2 that is not covered by the insulating material 3. The external electrode 4 is formed from a porous electrical conductor made of an electrically conductive material containing silver as the main material

10   and glass, while lead wires 6 are connected to the external electrodes 4.

[0083]

The multi-layer piezoelectric actuator according to the second embodiment is particularly characterized in that a

15   plurality of pillars 18 are provided to penetrate the internal electrode 2 and connect two piezoelectric layers 1 that oppose each other as shown in Fig. 3. By forming the pillars 18 from a hard material such as ceramics disposed between the piezoelectric layers 1, it is made possible to

20   increase the rigidity of the internal electrodes 2 and suppress the displacement of the internal electrodes 2 from being absorbed, thus achieving stable displacement. As a result, it is made possible to minimize the variation in the amount of displacement among products and improve the

25   reliability. Variation in the amount of displacement after

operation over a long period of time is also decreased, and reliability can be improved.

[0084]

It is also preferable that not less than 30% of the pillars 18 have diameter B in the section 22 of the junction between the pillars 18 and the piezoelectric layer 1 not smaller than 50% of the maximum diameter A of the pillars 18 as shown in Fig. 3. This constitution enables it to achieve more stable displacement. Specifically, when 30% or more of the pillars 18 have diameter B in the section 22 of the junction between the pillars 18 and the piezoelectric layer 1 that is not smaller than 50% of the maximum diameter A of the pillars 18, strength of the pillars 18 and the piezoelectric layer 1 is increased and rigidity also becomes higher. This makes it possible to suppress the difference in the amount of displacement among the products, and improve the reliability. It is also made possible to decrease the change in the amount of displacement after a long period of operation and improve durability. For a similar reason, it is more preferable that not less than 50% of the pillars 18 have diameter B in the section 22 of the junction between the pillars 18 and the piezoelectric layer 1 not smaller than 50% of the maximum diameter A of the pillars 18.

[0085]

Maximum diameter A and diameter B are measured as

follows. First, maximum diameter A and diameter B in the
section 22 of the junction between the pillars 18 and the
piezoelectric layer 1 are measured for each pillar 18 in a
photograph of a section of the multi-layer piezoelectric

5   element on a region near the internal electrode 2. Value of
(B/A) × 100 is calculated from these measurements, so as to
determine the ratio of diameter B in the section 22 of the
junction between the pillars 18 and the piezoelectric layer 1
to the maximum diameter A for each pillar 18. Proportion of

10   the pillars having this ratio not less than 50% to the number
of pillars measured is calculated. This operation is carried
out at ten points and the results are averaged.
[0086]

        According to the second embodiment, mean value of

15   minimum diameters of the pillars 18 is 0.2 μm or larger, more
preferably 0.3 μm or larger. This enables it to increase the
strength of the pillars 18 which become less likely to break.
As a result, variation in the amount of displacement is
suppressed, making it possible to decrease the change in the

20   amount of displacement after long period of operation and
improve durability.
[0087]

        In the multi-layer piezoelectric element of the present
invention, it is preferable that the number of pillars 18 per

25   1 mm in the section near the internal electrode 2 is from 5

to 150, more preferably from 10 to 100. This is because rigidity can be improved and the multi-layer piezoelectric element having high reliability with less variation in the amount of displacement can be made by providing such a number of pillars 18 as described above. The effect of providing the pillars is insufficient when the number of pillars 18 is less than 5. When the number of pillars 18 is more than 100, function of the internal electrodes 2 diminishes as resistance thereof increases such that heat is generated therefrom.

[0088]

It is also preferable that the difference in thermal expansion coefficient between the pillar 18 and the piezoelectric layer 1 is $3 \times 10^{-5}/°C$ or less, more preferably $2 \times 10^{-5}/°C$ or less. This decreases the internal stress between the piezoelectric layer 1 and the pillar 18, increases the strength of adhesion in the interface and improves the durability. When PZT is used in the piezoelectric layers 1, PZT, Al_2O_3, ZrO_2, TiO_2, SiO_2 or the like may be used as the material to form the pillars 18 having difference in thermal expansion coefficient not larger than $3 \times 10^{-5}/°C$.

[0089]

It is also preferable that the pillar 18 and the piezoelectric layer 1 are made of the same material. This

decreases the internal stress between the piezoelectric layer
1 and the pillar 18 further, increases the strength of
adhesion in the interface and improves the durability.
[0090]

5   The pillars 18 can be formed by mixing a powder of
material that makes the pillar 18 in the internal electrodes
2, and holding the temperature while raising the temperature
in the firing process at least once at a temperature that is
not lower than 80% of the maximum temperature of firing.
10   That is, unlike the conventional firing process, a
temperature that is not lower than 80% of the maximum
temperature of firing is maintained for a while after
degreasing, so that the powder of material that makes the
pillar 18 mixed in the internal electrodes 2 is influenced by
15   the surrounding metal composition and turns into such a state
that makes it easier for grains to grow. Then as the
material is fired at the maximum temperature, grains grow so
as to link between the piezoelectric layers 1, so that
pillars 18 are formed that penetrate the internal electrodes
20   2 and connect the piezoelectric layers 1 that oppose each
other via the internal electrode 2. Proportion of the powder
of material that makes the pillar 18 added to the internal
electrodes 2 is from 5 to 40% by weight. When more than 40%
by weight is added, resistance of the electrode may become
25   too high thus resulting in heat generation. When less than

5% by weight is added, the pillars cannot be formed

sufficiently, thus resulting in insufficient effect of

improving the rigidity of the internal electrode and making

it impossible to sufficiently improve the reliability and

5   durability.

[0091]

A method of manufacturing the multi-layer piezoelectric

element of the second embodiment will now be described below.

First, ceramic green sheets that would become the

10   piezoelectric layers 1 are made similarly to the first

embodiment.

Then a metal powder such as silver-palladium that

constitutes the internal electrode is mixed with at least one

kind of ceramic powder such as PZT, Al_2O_3, ZrO_2, TiO_2, SiO_2 as

15   the material to form the pillars 18, a binder and a

plasticizer are mixed to prepare an electrically conductive

paste. The electrically conductive paste is applied onto the

top surface of the ceramic green sheet by screen printing

method or the like to a thickness of 1 to 40 μm.

20   [0092]

A plurality of the green sheets having the electrically

conductive paste printed on the top surface thereof are

stacked one on another, with the stack being heated at a

predetermined temperature to remove the binder. After

25   holding the stack a temperature that is not lower than 80% of

the maximum temperature of firing for a while, the stack is

fired at the maximum temperature in a range from 900 to

1200°C. The length of period during which the temperature

not lower than 80% of the maximum temperature is maintained

5   is preferably longer than 0.25 hours, and may consist of two

or more steps. For example, the material may be heated in

multiple steps in which the temperature is held at a level

from 80% to 90% of the maximum temperature. It is necessary

to hold a temperature that is not lower than 80% of the

10   maximum temperature of firing for a while in order to cause

the pillars to grow. This enables it to firmly connect the

opposing piezoelectric layers. The maximum temperature is

set in a range from 900 to 1200°C because dense piezoelectric

layers cannot be formed at a temperature below 900°C, and

15   stress generated by the difference in shrinkage between the

electrodes and the piezoelectric layers becomes larger during

firing and causes cracks during continuous operation when the

maximum temperature is higher than 1200°C.

[0093]

20   Then a groove is formed between the internal electrode 2

of which end is not exposed and the side face in such a

configuration as the end of the internal electrode is exposed

in every other layer on the side face of the multi-layer

piezoelectric element, with the groove being filled with an

25   insulating material such as resin or rubber that has Young's

modulus lower than that of the piezoelectric layer 1. The groove 3 may be formed by means of a dicing apparatus or the like.

[0094]

Then the external electrodes 4 are formed similarly to the first embodiment.

Then the stack 10 having the external electrodes 4 formed thereon is immersed in a silicone rubber solution while deaerating the silicone rubber solution by evacuation, so as to fill the groove of the stack 10 with the silicone rubber. Then the stack 10 is pulled out of the silicone rubber solution and is coated with the silicone rubber on the side faces thereof. Then the silicon rubber that fills the groove and covers the side faces of the stack 10 is cured.

When lead sires are connected to the external electrodes 4, the multi-layer piezoelectric element of the present invention is completed.

[0095]

Then DC voltage of 0.1 to 3 kV/mm is applied between the pair of external electrodes 4 via the lead wires so as to apply polarization treatment to the stack 10, thereby to complete the multi-layer piezoelectric actuator as a product. When the lead wires are connected to an external voltage source and the voltage is supplied via the lead wires and the external electrodes 4 to the internal electrodes 2, the

piezoelectric layers 1 undergo a significant amount of displacement by the reverse piezoelectric effect, thus functioning as an automobile fuel injection valve that supplies fuel to an engine.

5   [0096]

In the multi-layer piezoelectric element constituted as described above, the internal electrodes 2 have high rigidity and improved bonding strength, thus enabling it to decrease the amount of displacement absorbed by the internal

10   electrodes. Also because delamination does not occur when subjected to continuous operation, change in the amount of displacement can be made smaller. As a result, a piezoelectric actuator that has high reliability and is free from malfunction can be provided.

15   The multi-layer piezoelectric element of the second embodiment is not limited to the examples described above, and various modifications may be made within the scope of the present invention.

[0097]

20   Third Embodiment

Figs. 5A and 5B show multi-layer piezoelectric element according to the third embodiment of the present invention. Fig. 5A is a perspective view and Fig. 5B is a sectional view showing the state of the piezoelectric layers, the internal

25   electrode layers, the protective sections and the dummy

layers being stacked one on another.

[0098]

The multi-layer piezoelectric element according to the third embodiment has the external electrodes 4 formed on a pair of opposing side faces of a stack 30 formed by stacking the piezoelectric layers 1 and the internal electrodes 2 alternately, where the internal electrodes 2 are provided so as to electrically connect to the external electrode 4 in every other layer. In the multi-layer piezoelectric element according to the third embodiment, the stack 30 has such a constitution as inactive protective sections 20 are formed by alternately stacking the piezoelectric layers 1 and the dummy layers 21 on the top and bottom of a stacked drive section 13.

[0099]

The multi-layer piezoelectric element of the third embodiment is, in particular, constituted such that the ratio of minimum distance A between the periphery of the dummy layer 21 and the side face of the stack to the width B of the inactive protective layer 20, A/B, is in a range from 0.01 to 0.08 in a cross section perpendicular to the direction of stacking of the stack 30. The invention related to the third embodiment has been completed based on finding that, by setting the minimum distance A and the width B of the inactive protective section 20 in the range described above, it is made possible to make a multi-layer piezoelectric

element of high reliability that does not undergo change in the characteristics after long period of operation.

[0100]

When the ratio A/B is less than 0.01, the region of junction between the piezoelectric layers becomes too small, and the stress generated in the dummy layer 21 by deformation during operation over a long period of time exceeds the force of connecting the piezoelectric layers, thus increasing the possibility of delamination to occur.

[0101]

When the ratio A/B is larger than 0.08, difference in the magnitude and profile of shrinkage between the inactive protective section 20 and the stacked drive section 13 during firing causes a significant strain between these members larger than the bonding strength between the piezoelectric layers. This results, in a worst case, in delamination after firing or delamination caused by operation over a long period of time.

[0102]

According to the present invention, the ratio A/B is preferably in a range from 0.02 to 0.07, more preferably from 0.03 to 0.06. This makes delamination of the inactive protective section 20 less likely to occur, thus improving durability.

The dummy layer 21 preferably contains metal. This

mitigates the stress generated between the piezoelectric layers 1 and enables it to operate over a long period of time with improved durability. The metal may be a metallic element such as Ag, Cu, Ni, Pd or the like, and an alloy

5   formed from one or more thereof. The dummy layer may also contain glass.

[0103]

It is preferable that the dummy layer 21 is formed from the same material as that of the internal electrode 2. This

10   causes the inactive protective section 20 and the stacked drive section 13 to behave substantially the same way during firing, so that stress is suppressed from being generated between these members, possibility of delamination is decreased and a piezoelectric element having improved

15   durability is obtained.

[0104]

Thickness of the piezoelectric layer 1 is preferably not less than 50 μm. The piezoelectric layer 1, when formed with such a thickness, can endure the stress generated therein so

20   as to prevent breaking.

It is also preferable that the dummy layer 21 contains an inorganic composition, that is at least one of metal oxide, nitride and carbide. Including the inorganic composition in the dummy layer 21 generates crosslinking of the inorganic

25   composition between the piezoelectric layers 1, making it

stronger against stress generated during firing or during use, so that delamination is less likely to occur and therefore durability is improved. For the inorganic composition, PZT, Al_2O_3, ZrO_2, TiO_2, SiO_2, TiN, Si_3N_4, AlN, SiC, TiC or the like

5   may be used.

[0105]

It is preferable that the dummy layer 21 contains 2% by weight or more inorganic composition. This makes the crosslinking between the piezoelectric layers 1 sufficient,

10   resulting in increased strength of joining the piezoelectric layers 1, decreased possibility of delamination and improved durability.

A method of manufacturing the multi-layer piezoelectric element of the third embodiment will now be described below.

15   According to this method, first, ceramic green sheet that would become the piezoelectric layers 1 is formed similarly to the first embodiment.

The green sheet is cut into an appropriate size and secured on a frame for controlling the ratio A/B.

20   [0106]

Then a metal powder such as silver-palladium that constitutes the internal electrode 2, a binder and a plasticizer are mixed to prepare an electrically conductive paste which is applied onto the top surface of the ceramic

25   green sheet by screen printing method or the like to a

thickness of 1 to 40 μm, thereby preparing the green sheet to form the stacked drive section 13.

Similarly, the dummy layer that contains silver-palladium or the like is formed on the top surface of the green sheet by screen printing method or the like to a thickness of 1 to 40 μm, thereby preparing the green sheet to form the inactive protective section 20. The printing operation is carried out while controlling the ratio A/B to a predetermined value taking into consideration the shrinkage caused by firing.

[0107]

In order to control the ratio A/B, a plurality of the inactive protective sections 20 are stacked on top and bottom of the green sheet to form the stacked drive section 13 with the electrically conductive paste being printed on the top surface thereof and the green sheet to form the inactive protective section 20, which are bonded together by applying a pressure. The minimum distance A between the periphery of the dummy layer 21 and the side face of the inactive protective 20 can be controlled by securing the green sheet onto the frame and bonding the inactive protective section 20 and the stacked drive section 13 together.

[0108]

Then the green sheet is cut into an appropriate size and is heated at a predetermined temperature to remove the binder,

before being fired at a temperature in a range from 900 to 1200°C thereby to make the multi-layer piezoelectric element.

The method of making the multi-layer piezoelectric element is not limited to that described above, and any manufacturing method may be employed as long as the minimum distance A between the periphery of the dummy layer 21 and the side face of the inactive protective 20 can be controlled.

The internal electrode 2 of which end is exposed on the side face of the multi-layer piezoelectric element and the internal electrode 2 of which end is not exposed are stacked alternately, while a groove 3 is formed in the piezoelectric layer 1 located between the internal electrode 2 of which end is not exposed and the external electrode 4, with the groove 3 being filled with an insulating material such as resin or rubber having Young's modulus lower than that of the piezoelectric material 1. The electrically conductive material that constitutes the external electrode 4 on the side faces of the stacked drive section 13 is preferably silver that has a low value of Young's modulus or an alloy based on silver, in consideration of the capability to sufficiently absorb the stress generated by the expansion and contraction of the actuator.

Then the external electrodes 4 are formed similarly to the first embodiment.

[0109]

Then the stacked drive section 13 having the external electrodes 4 formed thereon is immersed in a silicone rubber solution while deaerating the silicone rubber solution by evacuation, so as to fill the groove 3 of the stacked drive section 13 with the silicone rubber. Then the stacked drive section 13 is pulled out of the silicone rubber solution and is coated with the silicone rubber on the side faces of the stacked drive section 13. Then the silicon rubber that fills the groove 3 and covers the side faces of the column-like stack 13 is cured, thereby to complete the multi-layer piezoelectric element of the present invention.

[0110]

Then lead wires 6 are connected to the external electrodes 4, and DC voltage of 0.1 to 3 kV/mm is applied between the pair of external electrodes 4 via the lead wires 6 so as to apply polarization treatment to the stacked drive section 13, thereby to complete the multi-layer piezoelectric actuator that utilizes the multi-layer piezoelectric element of the present invention. When the lead wires 6 are connected to an external voltage source and the voltage is supplied via the lead wires and the external electrodes 4 to the internal electrodes 2, the piezoelectric layers 1 undergo a significant amount of displacement by the reverse piezoelectric effect so as to function, for example, as an automobile fuel injection valve that supplies fuel to an

engine.

[0111]

Preferred embodiment of the constitution including the internal electrodes, external electrodes and other components of the multi-layer piezoelectric element according to the first through third embodiments will now be described.

[0112]

<Internal electrode>

According to the present invention, it is preferable that the metal composition in the internal electrode 2 contains group VIII metal and/or group Ib metal as the main components. Since these metal compositions have high heat resistance and therefore allows the piezoelectric layers 1 that have a higher firing temperature and the internal electrodes 2 to be fired at the same time.

[0113]

It is preferable that such a metal composition is contained in the internal electrode 2 as the main component that proportion M1 (% by weight) of the group VIII metal and proportion M2 (% by weight) of the group Ib metal in the metal composition of the internal electrode 2 satisfy the relations $0 < M1 \leq 15$, $85 \leq M2 < 100$ and $M1 + M2 = 100$. This is because proportion of the group VIII metal higher than 15% by weight results in high specific resistance of the internal electrode 2 which causes the internal electrodes 2 to

generate heat when the multi-layer piezoelectric element is operated continuously over a long period of time. In order to suppress the group Ib metal contained in the internal electrode 2 from migrating into the piezoelectric layers 1,

5   it is preferable to control the proportion of the group VIII metal in a range from 0.001 to 15% by weight. For the purpose of improving the durability of the multi-layer piezoelectric element, proportion of the group VIII metal is preferably in a range from 0.1 to 10% by weight. In case

10   excellent heat conductivity and higher durability are required, proportion of the group VIII metal is preferably in a range from 0.5 to 9.5% by weight. In order to improve the durability further, proportion of the group VIII metal is preferably in a range from 2 to 8% by weight.

15   [0114]

Proportion of the group Ib metal is preferably 85% by weight or more because proportion of the group Ib metal lower than 85% by weight results in high specific resistance of the internal electrode 2 which causes the internal electrodes 2

20   to generate heat when the multi-layer piezoelectric element is operated continuously over a long period of time. In order to suppress the group Ib metal contained in the internal electrode 2 from migrating into the piezoelectric layers 1, it is preferable to control the proportion of the

25   group Ib metal in a range from 85 to 99.999% by weight. For

the purpose of improving the durability of the multi-layer piezoelectric element, proportion of the group Ib metal is preferably in a range from 90 to 99.9% by weight. In case higher durability is required, proportion of the group Ib metal is preferably in a range from 90.5 to 99.5% by weight. In order to improve the durability further, proportion of the group Ib metal is preferably in a range from 92 to 98% by weight.

[0115]

The group VIII metal and the group Ib metal in the internal electrode 2 can be identified by analytical method such as EPMA (Electron Probe Micro Analysis).

[0116]

Metal elements contained in the internal electrode 2 of the present invention are preferably the group VIII metal that is at least one kind selected from among Ni, Pt, Pd, Rh, Ir, Ru and Os, and the group Ib metal that is at least one kind selected from among Cu, Ag and Au, since such a metal composition is advantageous in volume production when the alloy powder synthesizing technology available today is employed.

[0117]

Further, it is preferable that the group VIII metal contained in the internal electrode 2 is at least one kind selected from among Pt and Pd, and the group Ib metal is at

least one kind selected from among Ag and Au. This composition makes it possible to form the internal electrode 2 having high heat resistance and low specific resistance.

[0118]

5   Further, it is preferable that the group VIII metal contained in the internal electrode 2 is Ni and the group Ib metal is Cu. This composition makes it possible to form the internal electrode 2 having higher heat resistance and high heat conductivity.

10   [0119]

Further it is preferable to add oxide, nitride or carbide along with the metallic component in the internal electrode 2. This increases the bonding strength between the internal electrode 2 and the piezoelectric material 1,

15   thereby improving the durability of the multi-layer piezoelectric element.

[0120]

It is preferable that the oxide described above includes perovskite type oxide consisting of $PbZrO_3$-$PbTiO_3$ as the main

20   component. Contents of oxide can be determined from the composition of the area ratio of the corresponding grains in the internal electrode measured on an SEM photograph of a section of the multi-layer piezoelectric element.

[0121]

25   The deviation in the composition of the internal

electrode 2 that is caused by the firing operation is preferably not larger than 5%. This is because a deviation larger than 5% in the composition of the internal electrode 2 caused by the firing operation causes a greater amount of the

5 metallic component contained in the internal electrode 2 to migrate into the piezoelectric layer 1, thus making it impossible for the internal electrode 2 to deform in conformity with the expansion and contraction of the multi-layer piezoelectric element during operation. The electrodes

10 can be restricted from becoming too hard by controlling the deviation in the composition of the electrode after the firing within 5%.

[0122]

The deviation in the composition of the internal

15 electrode 2 refers to the variation in the composition of the internal electrode 2 caused by evaporation of the elements that constitute the internal electrode 2 due to firing or diffusion thereof into the piezoelectric material 1.

[0123]

20 In the multi-layer piezoelectric element of the present invention, it is also preferable that the internal electrodes include voids and the voids occupy 5 to 70% of cross sectional area of the internal electrodes. This decreases the restrictive force exerted by the internal electrode on

25 the deformation of the piezoelectric material under the

effect of electric field, thereby increasing the amount of displacement of the piezoelectric material. It also provides such an advantage that stress generated in the internal electrode is mitigated by the voids, thereby improving the

5   durability of the device. In addition, while heat transfer within the device is predominantly carried by the internal electrodes, existence of the voids in the internal electrode mitigates the change in temperature within the device caused by rapid changes in the temperature outside of the device,

10 thus making the device more resistant to thermal shock.

[0124]

In the first through third embodiments, it is preferable that the internal electrodes 2 include voids and the ratio of area occupied by the voids to the entire sectional area

15 (hereinafter referred to as the void ratio) is from 5 to 70% in the section of the internal electrodes 2.

[0125]

When the multi-layer piezoelectric element is constituted by using the internal electrodes 2 that include

20 the voids as described above, the multi-layer piezoelectric element of high durability is obtained. When the void ratio in the internal electrodes 2 is less than 5%, the restrictive force exerted on the deformation of the piezoelectric material increases, resulting in insufficient effect of the

25 voids. Void ratio in the internal electrodes 2 more than 70%

is not desirable since it results in the internal electrodes
2 having electrical conductivity that is too low and strength
that is too weak. In order to improve durability of the
device, void ratio in the internal electrodes 2 is preferably
in a range from 7 to 70%. Greater amount of displacement and
high durability can be achieved by controlling the void ratio
in the internal electrodes 2 in a range from 10 to 60%.
[0126]

The void ratio in the section of the internal electrodes
2, which is the ratio of area occupied by the voids to the
entire sectional area of the internal electrodes 2 as
described above, can be determined as follows.
[0127]

The multi-layer piezoelectric element is cut along a
plane parallel to the direction of stacking. Total area of
one of the internal electrodes 2 exposed in the section and
the area occupied by the voids are measured while observing,
for example, under a microscope. Void ratio in the section
of the internal electrodes 2 ((Area occupied by the
voids)/Total area) × 100) is calculated from the ratio of
areas.
[0128]

The internal electrodes 2 that include the voids can be
made as follows.

First, two or more kinds of materials having different

melting points are prepared for the metal powders used to make the internal electrodes 2, so that voids are formed in the internal electrodes 2 after firing. Alloy may also be used as the metallic material depending on the application.

5   [0129]

The material is calcined at a temperature not lower than the melting point of the metal that has the lowest melting point among the metal powders used to make the internal electrodes 2 and not higher than the melting point of the

10   metal that has the highest melting point. When the material is calcined at such a temperature, the metal or alloy that has the melting point lower than the firing temperature among the metal powders that constitute the internal electrodes 2 melts and flows due to the capillary effect through the space

15   between the metal powders that have not melted, so as to leave voids where it originally existed. With this method, the void ratio in the internal electrodes 2 can be controlled to a desired value by adjusting the proportions of mixing the two or more kinds of metal powders used to make the internal

20   electrodes 2 and controlling the temperature.

[0130]

Voids in the internal electrodes 2 may also be formed by making use of minute spaces created between the particles of the metal powder when preparing the electrically conductive

25   paste used to form the internal electrodes 2, or the spaces

left by burning out of the binder contained in the electrically conductive paste.

[0131]

Alternatively, the voids in the internal electrode 2 may also be formed by adding a material, that has low wettability with regards to the materials that constitute the internal electrode 2, to the electrically conductive paste used in forming the internal electrode 2, or by coating the green sheet of the piezoelectric material, whereon the electrically conductive paste of the internal electrode 2 is to be printed, with a material that has low wettability with regards to the materials that constitute the internal electrode 2. For the material that has low wettability with regards to the materials that constitute the internal electrode 2, for example, BN can be used.

[0132]

<Piezoelectric layer 1>

It is further preferable that the piezoelectric material 1 includes perovskite type oxide as the main component. This is because the piezoelectric material 1 formed from perovskite type oxide such as barium titanate ($BaTiO_3$) has high piezoelectric strain constant d_{33} which enables it to increase the amount of displacement. This constitution also enables the piezoelectric material 1 and the internal electrode 2 to be fired at the same time. It is also

preferable that the piezoelectric material 1 contains perovskite type oxide consisting of $PbZrO_3-PbTiO_3$ that has a relatively high value of piezoelectric strain constant d_{33} as the main component.

5   [0133]

The firing temperature is preferably in a range from 900 to 1000°C. When the firing temperature is lower than 900°C, the firing process does not fully proceed, and it becomes difficult to make dense piezoelectric material 1. When the firing temperature is higher than 1000°C, larger stress is generated due to the difference in contraction between the internal electrode 2 and the piezoelectric material 1 when fired, thus resulting in cracks occurring during continuous operation of the multi-layer piezoelectric element.

15   [0134]

<Connection and insulation between internal electrode and external electrode>

It is preferable that the internal electrode 2 of which end is exposed on the side face of the multi-layer piezoelectric element of the present invention and the internal electrode 2 of which end is not exposed are stacked alternately, while the groove is formed in the piezoelectric layer located between the internal electrode 2 of which end is not exposed and the external electrode 4, with the groove being filled with an insulating material having Young's

modulus lower than that of the piezoelectric material 1. In the multi-layer piezoelectric element having such a constitution, stress generated by the displacement during operation can be mitigated and therefore heat generation from the internal electrodes 2 can be suppressed even during continuous operation.

[0135]

<External electrode 4>

According to the present invention, the external electrodes 4 are preferably formed from a porous electrical conductor having 3-dimensional mesh structure, as shown in Figs. 4A and 4B. Unless the external electrodes 4 are formed from a porous electrical conductor having 3-dimensional mesh structure, the external electrodes do not have flexibility and cannot follow the expansion and contraction of the multi-layer piezoelectric actuator, eventually causing breakage of the external electrodes 4 and/or contact failure between the external electrode 4 and the internal electrode 2. The 3-dimensional mesh structure means, rather than such a state as spherical voids are contained in the external electrodes 4, that the powders of electrically conductive material and glass that constitute the external electrodes 4 are baked at a relatively low temperature and therefore sintering reaction does not fully proceed so that the voids are connected to each other to a certain extent, thereby forming 3-dimensional

configuration of the powders of electrically conductive

material and glass that constitute the external electrodes 4

being bonded with each other.

[0136]

Void ratio in the external electrode 4 is preferably in

a range from 30 to 70% by volume. The void ratio means the

proportion of the volume occupied by the voids 4a in the

external electrodes 4. When the void ratio in the external

electrode 4 is less than 30%, the external electrodes 4 may

not be capable of enduring the stress generated by the

expansion and contraction of the multi-layer piezoelectric

actuator, eventually leading to breakage of the external

electrode 4. When the void ratio in the external electrode 4

is higher than 70%, resistance of the external electrode 4

becomes higher and the external electrode 4 may be broken due

to localized heating when a large current flows.

[0137]

It is also preferable that a glass-rich layer is formed

on the surface of the external electrode 4 on the side of the

surface of the piezoelectric layer 1. This is because,

without the glass-rich layer, it is difficult to bond the

glass component in the external electrodes 4, and firm

bonding between the external electrode 4 and the

piezoelectric layer 1 cannot be easily achieved.

[0138]

It is also preferable that softening point (°C) of the glass that constitutes the external electrode 4 is not higher than 4/5 times the melting point (°C) of the electrically conductive material that constitutes the internal electrode 2.

5   This is because, when the softening point of the glass that constitutes the external electrode 4 is higher than 4/5 times the melting point of the electrically conductive material that constitutes the internal electrode 2, the softening point of the glass that constitutes the external electrode 4

10   and the melting point of the electrically conductive material that constitutes the internal electrode 2 become approximate to each other. Such a condition results in coagulation of the electrically conductive material of the internal electrodes 2 and the external electrodes 4 that impedes the

15   joining through diffusion from taking place. Also it makes it impossible to set the baking temperature at a proper temperature for the glass component of the external electrode 4 to soften, resulting in failure to achieve sufficient strength of bonding by the softened glass. It is also

20   preferable that a glass-rich layer is formed on the surface of the external electrode 4 on the side of the surface of the piezoelectric layer 1. This is because, without the glass-rich layer, it is difficult to bond the glass component in the external electrodes 4, and firm bonding between the

25   external electrode 4 and the piezoelectric layer 1 cannot be

easily achieved.

[0139]

The glass that constitutes the external electrodes 4 is preferably amorphous. This is because the external electrodes 4 constituted from crystalline glass is not capable of absorbing the stress generated by the expansion and contraction of the actuator, and may be cracked.

It is also preferable that thickness of the external electrodes 4 is greater than thickness of the piezoelectric layer 1. This is because the external electrodes 4 thicker than the piezoelectric layer 1 has higher strength, resulting in increasing load on the junction between the external electrodes 4 and the piezoelectric layer 1, eventually causing contact failure.

[0140]

An electrical conductivity assisting member formed from an electrically conductive adhesive, including a metal mesh or a mesh-like metal sheet embedded therein, may be provided on the external surface of the external electrode 4. By providing the electrical conductivity assisting member on the external surface of the external electrode 4, it is made possible to cause a large current to flow in the electrical conductivity assisting member even when the device is operated at a high speed by supplying a large current to the actuator so as to decrease the current flowing in the

external electrodes 4, thereby preventing the external electrodes 4 from breaking due to localized heat generation and greatly improving durability. Moreover, by embedding the metal mesh or a mesh-like metal sheet in the electrically

5   conductive adhesive, it is made possible to prevent the electrically conductive adhesive from cracking.

[0141]

The metal mesh refers to a structure of entwined metal wires, and the mesh-like metal sheet refers to a metal sheet

10   with a number of holes punched therethrough.

It is further preferable that the electrically conductive adhesive that constitutes the electrical conductivity assisting member is polyimide resin containing electrically conductive particles dispersed therein.

15   [0142]

The electrically conductive particles are preferably silver powder. This is because the use of silver powder that has relatively low specific resistance as the electrically conductive particles makes it easier to suppress localized

20   heat generation by the electrically conductive adhesive. When silver powder that has relatively low specific resistance is dispersed in polyimide resin that has high heat resistance, the electrical conductivity assisting member can maintain low resistivity and high bonding strength even when

25   used at high temperatures. More preferably, the electrically

conductive particles are non-spherical particles having such

shapes as flakes or acicular particles. When the

electrically conductive particles are non-spherical particles

such as flakes or acicular particles, the electrically

conductive particles can be firmly entwined with each other,

thereby increasing the shear strength of the electrically

conductive adhesive.

[0143]

It is preferable that the multi-layer piezoelectric

element of the present invention comprises a single plate or

a stack of one or more layers. This constitution enables it

to either transform a pressure applied to the device into a

voltage or cause the device to displace by applying a voltage

to the device. As a result, even when unexpected stress is

generated during operation, stress can be mitigated by

distributing the stress and converting it into voltage, thus

making it possible to provide a piezoelectric actuator having

excellent durability and high reliability.

[0144]

The multi-layer piezoelectric element of the present

invention is not limited to those described above, and

various modifications may be made within the scope of the

present invention.

[0145]

While an example where the external electrodes 4 are

formed on the opposing side faces of the stack has been described above, a pair of external electrodes may be formed, for example, on adjacent side faces according to the present invention.

Also according to the present invention, the stack is not necessarily required to have a shape of rectangular prism, but may have various shapes such as cylinder, polygonal prism or the like.

[0146]

Fourth Embodiment

Fig. 6 shows the injection apparatus of the present invention, wherein the container 31 has the injection hole 33 formed at one end thereof, and the needle valve 35 that can open and close the injection hole 33 is housed in the container 31.

[0147]

The injection hole 33 is provided with a fuel passage 37 in communication therewith. The fuel passage 37 is connected to a fuel source that is provided outside of the apparatus, so as to receive supply of the fuel at a high pressure that remains always constant. When the needle valve 35 opens the injection hole 33, the fuel that fills the fuel passage 37 is injected at a predetermined level of high pressure into a fuel chamber of an internal combustion engine that is not shown in the drawings.

[0148]

The needle valve 35 has an enlarged top portion of a larger diameter so as to serve as a piston 41 that makes sliding motion in a cylinder 39 that is formed in the container 31. The piezoelectric actuator 43 is housed in the container 31.

[0149]

With the injection apparatus as described above, when the piezoelectric actuator 43 is caused to expand by a voltage applied thereto, the piston 41 is pressed so that the needle valve 35 plugs the injection hole 33 and shuts off the fuel supply. When the voltage is removed, the piezoelectric actuator 43 contracts and a Belleville spring 45 presses back the piston 41 so that the injection hole 33 communicates with the fuel passage 37 thereby allowing the fuel to be injected.

[0150]

The present invention relates to the multi-layer piezoelectric element and the injection apparatus, but is not limited to the embodiments described above. For example, the present invention can be applied to a fuel injection apparatus of automobile engine, a liquid ejecting apparatus of an ink jet printer or the like or a drive unit used in precision positioning device or vibration preventing device for an optical apparatus, or to sensor devices such as a sensor element mounted in combustion pressure sensor,

knocking sensor, acceleration sensor, load sensor, ultrasound sensor, pressure sensor, yaw rate sensor or the like, or used as a circuit component mounted in piezoelectric gyro, piezoelectric switch, piezoelectric transducer, piezoelectric breaker or the like, and is also applicable to other purposes, as long as the piezoelectric characteristic is utilized.

EXAMPLES

[0151]

Examples 1 through 3

The multi-layer piezoelectric actuator of the present invention was fabricated as described below in Examples 1 through 3.

First, a calcined powder of a piezoelectric ceramic material constituted from lead titanate zirconate ($PbZrO_3$–$PbTiO_3$) as the main component, a binder and a plasticizer were mixed to form a slurry which was formed into ceramic green sheets that would become the piezoelectric layer 1 having thickness of 150 μm by the doctor blade process.

[0152]

An electrically conductive paste, prepared by adding a binder to the silver-palladium alloy made with an arbitrary composition, was applied to one side of the ceramic green sheet by screen printing method to a thickness of 3 μm. Then 300 pieces of the ceramic green sheets were stacked and fired

at a temperature of 1000°C.

Then a groove measuring 50 μm in depth and 50 μm in
width was formed at the end of the internal electrode located
on the side face of the stack in every other layer, by means
5   of a dicing apparatus.

[0153]

Then 90% by volume of silver powder of flake-like
particles having mean particle size of 2 μm and 10% by volume
of amorphous glass powder having softening point of 640°C
10   containing silicon as the main component having mean particle
size of 2 μm were mixed, and 8 weight parts of a binder was
added to 100 weight parts in total of the silver powder and
the glass powder, so as to prepare the electrically
conductive silver-glass paste by fully mixing the powders.
15   The electrically conductive silver-glass paste thus prepared
was screen printed onto a release film. After drying, the
paste film was peeled off the release film to obtain a sheet
of electrically conductive silver-glass paste. Density of
the green sheet as measured by Archimedes method was 6.5
20   g/cm^3.

[0154]

The sheet of the silver-glass paste was transferred onto
the external electrode 4 surface of the stack and was baked
at 650°C for 30 minutes, thereby forming the external
25   electrode 4 from the porous electrically conductive material

having 3-dimensional mesh structure. Measurement of void ratio of the external electrode 4 by means of image analysis apparatus on a photograph of a cut surface of the external electrode 4 showed a void ratio of 40%.

5 [0155]

Then lead wires were connected to the external electrodes 4, and DC electric field of 3 kV/mm was applied between the positive and negative external electrodes 4 via the lead wires so as to apply polarization treatment for 15

10 minutes, thereby to complete the multi-layer piezoelectric actuator using the multi-layer piezoelectric element as shown in Fig. 1.

[0156]

Example 1

15 With the multi-layer piezoelectric actuator of the present invention made by controlling resistance of the device and the induction loss (tan δ) of the piezoelectric material 1 to a low level, rate of change in the amount of displacement of the device, rate of change in thickness of

20 the piezoelectric layer, rate of change in resistance of the device and rate of change in device temperature after continuous operation of the multi-layer piezoelectric actuator were measured. These measurements were examined against the degree of deterioration of the multi-layer

25 piezoelectric actuator caused by long period of operation.

[0157]

The degree of deterioration is determined as follows. The amount of displacement of the device after operating the multi-layer piezoelectric actuator for an arbitrary number of cycles (the amount of displacement after continuous operation) is counted. Then the amount of displacement of the device after operating the multi-layer piezoelectric actuator for a predetermined number of cycles (the amount of displacement after a long period of operation) is counted. The degree of deterioration is defined as the ratio of the change in the amount of displacement after a long period of operation to the amount of displacement after continuous operation. This value enables it to examine the progress of deterioration, by operating the multi-layer piezoelectric actuator, that has been operated an arbitrary number of times, further for a predetermined number of cycles.

[0158]

As Comparative Example, sample was made of which rate of change in displacement of the element or rate of change in resistance of the element before and after continuous operation of the multi-layer piezoelectric actuator exceeded 5%.

[0159]

When a DC voltage of 170 V was applied to the multi-layer piezoelectric actuators made as described above, all

the multi-layer piezoelectric actuators underwent displacement of 45 μm in the direction of stacking. Operation test was conducted on the multi-layer piezoelectric actuators by applying an AC voltage varying between 0 V and

5 +170 V at frequency of 150 Hz at room temperature to carry out continuous operation of 1×10^9 cycles. Long-term operation test of 1×10^{10} cycles was also conducted. The results are shown in Table 1. The ratio of change in thickness of the piezoelectric layer was determined by

10 observing the side face of the multi-layer piezoelectric element under an SEM before operation to measure the thickness of the piezoelectric layer at 10 points and average the measurements, while measuring the thickness of the piezoelectric layer after the operation at the same points

15 and averaging the measurements.

[0160]
Table 1-1

No.	Resistance of internal electrode normalized to resistance of 100% silver	Induction loss tan δ (%) of the piezoelectric material	Amount of displacement (μm) in initial state = A	Change (%) in device temperature after continuous operation (1 × 10^9 cycles)
1	2	0.5	45.0	0.0
2	3	0.5	45.0	0.2
3	3.5	0.5	45.0	0.4
4	4	0.5	45.0	0.6
5	5	0.5	45.0	0.8
6	8	0.5	45.0	1.2
7	10	0.5	45.0	2.6
8	5	1.0	45.0	4.5
*9	5	1.5	45.0	6.2

[0161]
Table 1-2

No.	Change (%) in thickness of piezoelectric layer after continuous operation (1 × 10^9 cycles)	Change (%) in resistance of element after continuous operation (1 × 10^9 cycles)	Maximum displacement (μm) after continuous operation (1 × 10^9 cycles) = B
1	0.0	0.0	45.0
2	0.2	0.2	44.9
3	0.4	0.4	44.8
4	0.6	0.7	44.7
5	0.8	0.9	44.6
6	1.2	1.3	44.4
7	2.6	2.9	43.7
8	5.0	5.0	42.8
*9	6.4	6.9	41.9

[0162]

Table 1-3

No.	Ratio of change (%) in displacement after continuous operation to initial displacement = |(A-B)/A × 100|	Displacement after long-term operation (1 × 10^{10} cycles) (μm) = C	Degree of deterioration (%) = |(B − C)/B × 100|
1	0.0	45.0	0.00
2	0.2	44.9	0.00
3	0.4	44.7	0.22
4	0.7	44.6	0.22
5	0.9	44.4	0.45
6	1.3	44.1	0.68
7	2.9	43.2	1.14
8	5.0	41.9	2.10
*9	6.9	38.5	8.11

In the tables described above, sample marked with * is comparative example.

[0163]

Table 1 shows that sample No. 9 that is a comparative example showed a change in displacement more than 5% after continuous operation. As a result, displacement of the multi-layer piezoelectric actuator measured after long-term operation of 1 × 10^{10} cycles following continuous operation of 1 × 10^9 cycles showed significant decrease in the displacement after long-term operation of 1 × 10^{10} cycles over the displacement after continuous operation of 1 × 10^9 cycles, indicating an increasing degree of deterioration and difficulty in continuously operating the multi-layer

piezoelectric actuator.

[0164]

   With the change in resistance of the device more than 5% after continuous operation, displacement of the multi-layer piezoelectric actuator measured after long-term operation of 1×10^{10} cycles following continuous operation of 1×10^9 cycles showed significant decrease in the displacement after long-term operation of 1×10^{10} cycles over the displacement after continuous operation of 1×10^9 cycles, indicating an increasing degree of deterioration and difficulty in continuously operating the multi-layer piezoelectric actuator.

[0165]

   With the change in dimension of the piezoelectric layer more than 5% after continuous operation, displacement of the multi-layer piezoelectric actuator measured after long-term operation of 1×10^{10} cycles following continuous operation of 1×10^9 cycles showed significant decrease in the displacement after long-term operation of 1×10^{10} cycles over the displacement after continuous operation of 1×10^9 cycles, indicating an increasing degree of deterioration and difficulty in continuously operating the multi-layer piezoelectric actuator.

[0166]

   Samples Nos. 1 through 8 of Example 1 according to the present invention were multi-layer piezoelectric actuators

having changes in displacement of the element within 5% after
continuous operation, in contrast, showing an amount of
displacement required for the multi-layer piezoelectric
actuator without significantly decreasing the amount of

5   displacement of the device even when operated for 1×10^{10}
cycles after continuous operation of 1×10^9 cycles, and the
multi-layer piezoelectric actuator having excellent
durability without thermal excursion and malfunction was made.
[0167]

10   Similarly, samples Nos. 1 through 8 of Example 1 also
had changes in resistance of the device within 5% after
continuous operation, showing an amount of displacement
required for the multi-layer piezoelectric actuator without
significantly decreasing the amount of displacement of the

15   device even when operated for 1×10^{10} cycles after
continuous operation of 1×10^9 cycles, and the multi-layer
piezoelectric actuator having excellent durability without
thermal excursion and malfunction was made.
[0168]

20   Similarly, samples Nos. 1 through 8 of Example 1 had
changes in dimension of the piezoelectric layer within 5%
after continuous operation, showing an amount of displacement
required for the multi-layer piezoelectric actuator without
significantly decreasing the amount of displacement of the

25   device even when operated for 1×10^{10} cycles after

continuous operation of 1×10^9 cycles, and the multi-layer
piezoelectric actuator having excellent durability without
thermal excursion and malfunction was made.

[0169]

Example 2

In addition to the manufacturing method described above,
the multi-layer piezoelectric actuator of the present
invention made by controlling resistance of the device and
the induction loss (tan δ) of the piezoelectric material 1 to
a low level, maximum change in the amount of displacement of
the device, maximum change in resistance of the device and
change in device temperature after continuous operation of
the multi-layer piezoelectric actuator were measured. These
measurements were examined against durability of the multi-
layer piezoelectric actuator.

[0170]

The degree of deterioration is determined as follows.
The amount of displacement of the element after operating the
multi-layer piezoelectric actuator for an arbitrary number of
cycles (the amount of displacement after continuous
operation) is measured. Then the amount of displacement of
the device after operating the multi-layer piezoelectric
actuator for a predetermined number of cycles (the amount of
displacement after a long period of operation) is measured.
The degree of deterioration is defined as the ratio of the

change in the amount of displacement after a long period of operation to the amount of displacement after continuous operation. This value enables it to examine the progress of deterioration, by operating the multi-layer piezoelectric actuator, that has been operated an arbitrary number of times, further for a predetermined number of cycles.

[0171]

As Comparative Example, samples were made of which changes in displacement or change in resistance of the device during continuous operation of the multi-layer piezoelectric actuator exceeded 5%.

[0172]

When a DC voltage of 170 V was applied to the multi-layer piezoelectric actuators made as described above, all the multi-layer piezoelectric actuators underwent displacement of 45 μm in the direction of stacking. Operation test was conducted on the multi-layer piezoelectric actuators by applying an AC voltage varying between 0 V and +170 V at frequency of 150 Hz at room temperature to carry out continuous operation of 1×10^9 cycles. The results are shown in Table 2.

[0173]

Table 2-1

No.	Resistance of internal electrode normalized to resistance of 100% silver	Induction loss tan δ (%) of the piezoelectric material	Amount of displacement (μm) in initial state = A
1	2	0.5	45.0
2	3	0.5	45.0
3	4	0.5 .	45.0
4	5	0.5	45.0
5	8	0.5	45.0
6	10	0.5	45.0
7	5	1.5	45.0
*8	8	1.5	45.0
*9	10	2.5	45.0

[0174]

Table 2-2

No.	Maximum change (%) in temperature of element during continuous operation (1 × 10^8 cycles)	Maximum change (%) in resistance of element during continuous operation (1 × 10^8 cycles)	Maximum displacement (μm) during continuous operation (1 × 10^8 cycles) = B
1	0.0	0.0	45.0
2	0.2	0.2	44.9
3	0.4	0.4	44.8
4	0.6	0.7	44.7
5	0.8	0.9	44.6
6	1.8	2.0	44.1
7	4.5	5.0	42.8
*8	7.0	7.8	41.5
*9	5.0	5.6	47.5

[0175]

Table 2-3

No.	Maximum rate of change (%) in displacement during continuous operation to initial displacement = $\lvert (A-B)/A \times 100 \rvert$	Displacement (μm) during continuous operation (1 × 10^9 cycles) = C	Degree of deterioration (%) = $\lvert (B - C)/B \times 100 \rvert$
1	0	45.0	0.00
2	0.2	44.9	0.00
3	0.4	44.7	0.22
4	0.7	44.6	0.22
5	0.9	44.4	0.45
6	2.0	43.7	0.91
7	5.0	41.9	1.99
*8	7.8	38.0	8.43
*9	5.6	Thermal excursion occurred	–

In the tables described above, sample marked with * is out of the scope of the present invention.

[0176]

Table 2 shows that samples Nos. 8 and 9 that were comparative examples showed maximum change in displacement more than 5% during continuous operation. As a result, displacement of the multi-layer piezoelectric actuator measured after continuous operation of 1 × 10^9 cycles showed significant decrease in the displacement of the device after continuous operation of 1 × 10^9 cycles compared to the maximum displacement of the device during continuous operation of 1 × 10^8 cycles, indicating an increasing degree of deterioration. Sample No. 9 experienced thermal excursion

resulting in destruction of the element, making it difficult to carry out continuous operation of the multi-layer piezoelectric actuator.

[0177]

5   With maximum change in resistance of the element more than 5% during continuous operation, displacement of the multi-layer piezoelectric actuator measured after long-term operation of 1×10^9 cycles showed significant decrease in the displacement of the device compared to the maximum

10   displacement of the device during continuous operation of 1×10^8 cycles after continuous operation of 1×10^9 cycles, indicating an increasing degree of deterioration and difficulty in continuously operating the multi-layer piezoelectric actuator.

15   [0178]

      Samples Nos. 1 through 7 of Example 2 according to the present invention were multi-layer piezoelectric actuators having maximum changes in displacement of the device within 5% after continuous operation, showing an amount of

20   displacement required for the multi-layer piezoelectric actuator without significantly decreasing the amount of displacement of the device even after continuous operation of 1×10^9 cycles, and the multi-layer piezoelectric actuator having excellent durability without thermal excursion and

25   malfunction were made.

[0179]

Samples Nos. 1 through 7 of Example 2, having changes in resistance of the device within 5% after continuous operation, showed amount of displacement required for the multi-layer piezoelectric actuator after continuous operation of 1×10^9 cycles, and enabled it to make the multi-layer piezoelectric actuator having excellent durability without thermal excursion and malfunction.

[0180]

Example 3

Multi-layer piezoelectric actuators having the internal electrodes 2 formed from electrode materials of various compositions were made by the manufacturing method described above. Maximum change in the amount of displacement of the multi-layer piezoelectric actuator during continuous operation was measured, and relation between the composition of electrode material of the internal electrodes 2 and the degree of deterioration of the multi-layer piezoelectric actuator after continuous operation was examined.

[0181]

When a DC voltage of 170 V was applied to the multi-layer piezoelectric actuators made as described above, all the multi-layer piezoelectric actuators underwent displacement of 45 μm in the direction of stacking. Operation test was conducted on the multi-layer piezoelectric

actuators by applying an AC voltage varying between 0 V and +170 V at frequency of 150 Hz at room temperature to carry out continuous operation of 1×10^9 cycles. The results are shown in Table 3.

[0182]

Table 3-1

No	Pd content in metal of internal electrode (% by weight)	Ag content in metal of internal electrode (% by weight)	Cu content in metal of internal electrode (% by weight)	Ni content in metal of internal electrode (% by weight)
1	0	100	0	0
2	0.001	99.999	0	0
3	0.01	99.99	0	0
4	0.1	99.9	0	0
5	0.5	99.5	0	0
6	1	99	0	0
7	2	98	0	0
8	4	95	1	0
9	5	95	0	0
10	8	92	0	0
11	9	91	0	0
12	9.5	90.5	0	0
13	10	90	0	0
14	15	85	0	0
15	0	0	100	0
16	0	0	99.9	0.1
17	0	0	0	100
18	20	80	0	0
19	30	70	0	0

[0183]

Table 3-2

No.	Rate of change (%) in displacement after continuous operation to initial displacement	Degree of deterioration (%)
1	Damaged by migration	−
2	0.7	0.22
3	0.7	0.22
4	0.4	0.22
5	0.2	0.00
6	0.2	0.00
7	0	0.00
8	0	0.00
9	0	0.00
10	0	0.00
11	0.2	0.00
12	0.2	0.00
13	0.4	0.22
14	0.7	0.22
15	0.2	0.00
16	0	0.00
17	0.4	0.22
18	0.9	0.45
19	0.9	0.45

[0184]

5   As shown in Table 3, sample No. 1 comprising the

internal electrode 2 formed from 100% silver underwent silver

migration that damaged the multi-layer piezoelectric actuator,

making it difficult to carry out continuous operation.

Samples Nos. 18 and 19, comprising the internal

electrode 2 containing metal composition with more than 15%

by weight of VIII metal and less than 85% by weight of Ib

5   metal, experienced increasing deterioration due to continuous

operation, thus resulting in lower durability of the multi-

layer piezoelectric actuator.

[0185]

Samples Nos. 2 through 17 of Example 3 of the present

10   invention, comprising the internal electrode 2 having such a

metal composition that proportion M1 (% by weight) of the

group VIII metal and proportion M2 (% by weight) of the group

Ib metal satisfied the relations $0 < M1 \leq 15$, $85 \leq M2 < 100$

and $M1 + M2 = 100$, in contrast, had lower specific resistance

15   of the internal electrode 2 so as to suppress the heat

generation from the internal electrodes 2 during continuous

operation, thus provided the multi-layer piezoelectric

actuator showing stable amount of displacement of the device.

[0186]

20   The present invention is not limited to Example

described above, and various modifications may be made within

the scope of the present invention.

[0187]

Example 4

25   The multi-layer piezoelectric actuator of the present

invention was fabricated as described below in Example 4.

[0188]

First, a column-like stack was made. Piezoelectric layers were formed from lead titanate zirconate ($PbZrO_3$-

5      $PbTiO_3$) to a thickness of 150 μm, and internal electrodes 2 were formed thereon to a thickness of 3 μm. Then 300 pieces each of the piezoelectric layers and the internal electrodes were stacked. The internal electrodes were formed from a mixed powder of metal (for example, 90Ag-10Pd) and ceramics

10   as shown in Table 4. For the ceramic powder, PZT, ZrO_2, TiO_2, a mixture of PZT and ZrO_2, or a mixture of PZT and TiO_2 is preferably used. The materials shown in Table 4-3 were used in proportions shown in the table, in this Example. Ceramic powder consisting of column-like particles having diameter of

15   1.5 μm or smaller and aspect ratio of 3 or less was used. After degreasing at a temperature from 400 to 700°C, the stack was held at 850°C for 20 minutes and fired at a temperature of 1000°C to obtain the sintered material. In case the internal electrodes were made of Ni, the stack was

20   degreased at a temperature from 400 to 700°C, held at 1050°C for 20 minutes and fired at a temperature of 1200°C to obtain the sintered material.

[0189]

Then a groove measuring 50 μm in depth and 50 μm in

25   width was formed at the end of the internal electrode located

on the side face of the column-like stack in every other layer, by means of a dicing apparatus.

Then 90% by volume of silver powder of flake-like particles having mean particle size of 2 μm and 10% by volume of amorphous glass powder having softening point of 640°C containing silicon as the main component having mean particle size of 2 μm were mixed, and 8 weight parts of a binder was added to 100 weight parts in total of the silver powder and the glass powder, so as to prepare the electrically conductive silver-glass paste by fully mixing the powders. The electrically conductive silver-glass paste thus prepared was screen printed onto a release film. After drying, the paste film was peeled off the release film to obtain a sheet of electrically conductive silver-glass paste. Density of the green sheet as measured by Archimedes method was 6.5 g/cm^3.

[0190]

The sheet of the silver-glass paste was transferred onto the external electrode surface of the column-like stack and was baked at 650°C for 30 minutes, thereby forming the external electrode from the porous electrically conductive material having 3-dimensional mesh structure. Measurement of void ratio of the external electrode by means of image analysis apparatus on a photograph of a cut surface of the external electrode showed a void ratio of 40%.

Then lead wires were connected to the external

electrodes, and DC electric field of 3 kV/mm was applied

between the positive and negative external electrodes via the

lead wires so as to apply polarization treatment for 15

5   minutes, thereby to complete the multi-layer piezoelectric

actuator using the multi-layer piezoelectric element as shown

in Fig. 1.

[0191]

With a DC voltage of 170 V applied to the multi-layer

10   piezoelectric actuators comprising the multi-layer

piezoelectric element made as described above, displacements

of the samples were measured, and variation in the

displacement was calculated with the results shown in Table 4.

Operation test was conducted on the multi-layer piezoelectric

15   actuators by applying an AC voltage varying between 0 V and

+170 V at frequency of 150 Hz at room temperature.

[0192]

DC voltage of 170 V was applied to the multi-layer

piezoelectric actuators comprising the multi-layer

20   piezoelectric elements that reached 1×10^9 cycles of

operation, and displacement of each sample was measured

thereby to determine the change in displacement after the

operation.   Specifically, the amount of displacement before

the operation test was divided by the amount of displacement

25   after the operation test, and the result was multiplied by

100 thus giving a value in percentage.

Diameter and number of the pillars that penetrated the internal electrode and connected the piezoelectric layers were measured as follows.

5   [0193]

Proportion of the pillars that had diameters in the section of junction not smaller than 50% of the maximum diameter was determined as follows. With a length of 1 mm measured in a photograph of a section of the multi-layer piezoelectric element on a region near the internal electrode 2 as shown in Fig. 2, maximum diameter A and diameter B in the section 22 of the junction between the pillars 18 and the piezoelectric layer 1 were measured for each pillar 18. Value of (B/A) × 100 was calculated from these measurements, so as to determine the ratio of diameter B in the section 22 of the junction between the pillars 18 and the piezoelectric layer 1 to the maximum diameter A for each pillar 18. Proportion by percentage of the pillars having this ratio not less than 50% to the number of pillars measured was calculated. This operation was carried out at ten points and the results are averaged. Minimum diameter of the pillar was also measured similarly to the above at 10 points.

Results of the measurements described above, materials of the internal electrodes and the difference in thermal expansion coefficient between the piezoelectric layer and the

pillar are shown in Table 4.

[0194]

Table 4-1

No.	Pillar	Proportion of pillars having diameters in junction not smaller than 50% of maximum diameter	Average of minimum diameters of the pillars	Number of pillars per 1 mm
	−	%	μ m	Pieces
1	Provided	20	1	65
2	Provided	30	1	77
3	Provided	50	1	83
4	Provided	70	1	76
5	Provided	90	1	68
6	Provided	50	0.1	95
7	Provided	50	0.2	84
8	Provided	50	0.5	63
9	Provided	50	1	61
10	Provided	50	3	50
11	Provided	50	5	34
12	Provided	50	2	5
13	Provided	50	2	11
14	Provided	50	2	54
15	Provided	50	2	99
16	Provided	50	2	148
17	Provided	50	1	84
18	Provided	50	1	90
19	Provided	50	1	79
20	Provided	50	1	76
21	Provided	50	1	86
22	Provided	50	1	83
23	Provided	50	1	76
24	Provided	50	1	89
25	Provided	50	1	83
26	None	−	−	−

[0195]

Table 4-2

No.	Difference in thermal expansion coefficient between piezoelectric layer and pillar × 10^{-6}/℃	Materials of piezoelectric layer and pillar	Material of internal electrode
1	0	Same	90Ag-10Pd
2	0	Same	90Ag-10Pd
3	0	Same	90Ag-10Pd
4	0	Same	90Ag-10Pd
5	0	Same	90Ag-10Pd
6	0	Same	90Ag-10Pd
7	0	Same	90Ag-10Pd
8	0	Same	90Ag-10Pd
9	0	Same	90Ag-10Pd
10	0	Same	90Ag-10Pd
11	0	Same	90Ag-10Pd
12	0	Same	90Ag-10Pd
13	0	Same	90Ag-10Pd
14	0	Same	90Ag-10Pd
15	0	Same	90Ag-10Pd
16	0	Same	90Ag-10Pd
17	2	Different	90Ag-10Pd
18	5	Different	90Ag-10Pd
19	6	Different	90Ag-10Pd
20	0	Same	85Ag-15Pd
21	0	Same	95Ag-5Pd
22	0	Same	99Ag-1Pd
23	0	Same	99.9Ag-0.1Pd
24	0	Same	100Cu
25	0	Same	100Ni
26	−	−	70Ag-30Pd

Table 4-3

No.	Material of pillar	Proportion (% by weight)
1	PZT	20
2	PZT	23
3	PZT	24
4	PZT	22
5	PZT	20
6	PZT	27
7	PZT	24
8	PZT	19
9	PZT	19
10	PZT	16
11	PZT	12
12	PZT	5
13	PZT	6
14	PZT	17
15	PZT	28
16	PZT	40
17	PZT20% + $ZrO_2$80%	24
18	PZT50% + $ZrO_2$50%	26
19	PZT50% + $TiO_2$50%	23
20	PZT	22
21	PZT	25
22	PZT	24
23	PZT	22
24	PZT	26
25	PZT	24
26	−	−

[0196]

Table 4-4

No.	Variation (%) in displacement	Ratio of change (%) in displacement after continuous durability test
1	10	5
2	8	4
3	5	2.5
4	5	1
5	4	0.5
6	8	4
7	7	4
8	6	3
9	5.5	2.5
10	4	1
11	3	0.5
12	7	4
13	6	3
14	4	2
15	3	0.5
16	2	0.5
17	3	0.5
18	3	0.5
19	3	0.5
20	3	1
21	3	0.5
22	3	0.5
23	3	0.5
24	3	0.5
25	3	0.5
26	20	10

[0197]

Samples Nos. 1 through 25 of Example 4 of the present invention having the pillars that penetrated the internal electrode and connected the piezoelectric layers via the internal electrode showed variation in the initial displacement not greater than 10%, smaller than that of Comparative Example (No. 26). Change in displacement after the continuous durability test was also small, within 5%, thus showing higher reliability and higher durability than the Comparative Example.

Samples Nos. 2 through 25 of Example 4 where 30% or more of the pillars had diameter in the junction not smaller than 50% of the maximum diameter, in particular, showed variation in the initial displacement of 8% or less and even smaller change in displacement after the continuous durability test, within 4%, thus showing even higher reliability and higher durability.

[0198]

Samples Nos. 3 through 5 and 7 through 25 of Example 4 where 50% or more of the pillars had diameter in the junction not smaller than 50% of the maximum diameter and that mean value of minimum diameters of the pillars was 0.2 µm, in particular, showed even smaller variation in the initial displacement of 7% or less, thus showing even higher reliability.

Sample No. 26 that was out of the scope of the present invention and was not provided with the pillars, in contrast, showed large variation of 20% in the initial displacement and the displacement after continuous durability test also showed

5   large variation of 10%, indicating lower characteristics than the sample of the present invention in reliability and durability.

[0199]

Example 5

10   The multi-layer piezoelectric actuator of the present invention was made in Example 5 as described below.

First, a calcined powder of a piezoelectric ceramic material constituted from lead titanate zirconate ($PbZrO_3$-$PbTiO_3$), a binder and a plasticizer were mixed to form a

15   slurry. The slurry was formed into ceramic green sheets having thickness of 150 μm that would become the piezoelectric layers 1 by doctor blade process.

[0200]

The ceramic green sheets were coated on one side thereof

20   with a paste selected from among an electrically conductive paste consisting of silver-palladium alloy with a binder added thereto, an electrically conductive paste consisting of Ag with a binder added thereto, an electrically conductive paste consisting of Cu with a binder added thereto and an

25   electrically conductive paste consisting of Ni with a binder

added thereto by screen printing to a thickness of 3 μm, thus
preparing 300 sheets with the electrically conductive paste
printed thereon, to be used in forming the stack. Other
green sheets were prepared to form the protective section.

5   30 sheets for the protective section, 300 sheets for the
stack and 30 sheets for the protective section were stacked
successively and pressed, before being fired at 1000°C.

[0201]

Then a groove measuring 50 μm in depth and 50 μm in

10   width was formed at the end of the internal electrode located
on the side face of the stack in every other layer, by means
of a dicing apparatus.

[0202]

Then 90% by volume of silver powder of flake-like

15   particles having mean particle size of 2 μm and 10% by volume
of amorphous glass powder having softening point of 640°C
containing silicon as the main component having mean particle
size of 2 μm were mixed, and 8 weight parts of a binder was
added to 100 weight parts in total of the silver powder and

20   the glass powder, so as to prepare the electrically
conductive silver-glass paste by fully mixing the powders.
The electrically conductive silver-glass paste thus prepared
was screen printed onto a release film. After drying, the
paste film was peeled off the release film to obtain a sheet

25   of electrically conductive silver-glass paste. Density of

the green sheet as measured by Archimedes method was 6.5 g/cm^3.

[0203]

The sheet of the silver-glass paste was transferred onto the external electrode surface of the stack and was baked at 650°C for 30 minutes, thereby forming the external electrode from the porous electrically conductive material having 3-dimensional mesh structure. Measurement of void ratio of the external electrode by means of image analysis apparatus on a photograph of a cut surface of the external electrode showed a void ratio of 40%.

[0204]

Then lead wires were connected to the external electrodes, and DC electric field of 3 kV/mm was applied to the positive and negative external electrodes via the lead wires so as to apply polarization treatment for 15 minutes, thereby to complete the multi-layer piezoelectric actuator using the multi-layer piezoelectric element as shown in Fig. 5.

With a DC voltage of 170 V applied to the multi-layer piezoelectric element made as described above, displacements of 45 μm in the direction of stacking was observed. Operation test was conducted on the multi-layer piezoelectric elements by applying an AC voltage varying between 0 V and +170 V at frequency of 150 Hz at room temperature.

[0205]

Failure rate of the multi-layer piezoelectric element was determined as the number of samples that failed before undergoing 1×10^9 cycles of continuous operation.

5   The results are shown in Table 5. Thickness of the piezoelectric layer of the protective section was varied from 50 to 200 μm as shown in Table 5, and the dummy layer was formed from one of silver-palladium alloy, silver, copper and nickel. The dummy layer contained PZT as an inorganic

10   composition.

[0206]

Table 5-1

No.	A/B	Dummy layer
1	0.04	99.99Ag-0.01Pd
2	0.04	99Ag-1Pd
3	0.04	95Ag-5Pd
4	0.04	90Ag-10Pd
5	0.04	70Ag-30Pd
6	0.04	50Ag-50Pd
7	0.005	90Ag-10Pd
8	0.01	90Ag-10Pd
9	0.02	90Ag-10Pd
10	0.03	90Ag-10Pd
11	0.05	90Ag-10Pd
12	0.06	90Ag-10Pd
13	0.07	90Ag-10Pd
14	0.08	90Ag-10Pd
15	0.09	90Ag-10Pd
16	0.02	95Ag-5Pd
17	0.08	95Ag-5Pd
18	0.04	90Ag-10Pd
19	0.04	90Ag-10Pd
20	0.04	90Ag-10Pd
21	0.04	90Ag-10Pd
22	0.04	90Ag-10Pd
23	0.04	90Ag-10Pd
24	0.04	90Ag-10Pd
25	0.04	90Ag-10Pd
26	0.04	90Ag-10Pd
27	0.04	100Ag
28	0.04	100Cu
29	0.04	100Ni
30	0.04	Glass

[0207]

Table 5-2

No.	Internal electrode	Thickness (μm) of piezoelectric layer	Inorganic composition content (% by weight) in dummy layer	Failure rate (%) after continuous durability test
1	Same as the dummy layer	100	20	0.3
2	Same as the dummy layer	100	20	0.1
3	Same as the dummy layer	100	20	0.2
4	Same as the dummy layer	100	20	0.2
5	Same as the dummy layer	100	20	0.4
6	Same as the dummy layer	100	20	0.8
7	Same as the dummy layer	100	20	3
8	Same as the dummy layer	100	20	2
9	Same as the dummy layer	100	20	1
10	Same as the dummy layer	100	20	0.5
11	Same as the dummy layer	100	20	0.4
12	Same as the dummy layer	100	20	0.5
13	Same as the dummy layer	100	20	0.8
14	Same as the dummy layer	100	20	2
15	Same as the dummy layer	100	20	3.5
16	Same as the dummy layer	100	20	0.8
17	Same as the dummy layer	100	20	1.8
18	Same as the dummy layer	50	20	0.2
19	Same as the dummy layer	70	20	0.2
20	Same as the dummy layer	150	20	0.3
21	Same as the dummy layer	200	20	0.2
22	Same as the dummy layer	100	2	0.4
23	Same as the dummy layer	100	10	0.2
24	Same as the dummy layer	100	30	0.2
25	Same as the dummy layer	100	40	0.4
26	70Ag-30Pd	100	20	1
27	Same as the dummy layer	100	20	0.2
28	Same as the dummy layer	100	20	0.2
29	Same as the dummy layer	100	20	0.2
30	70Ag-30Pd	100	20	1

[0208]

Table 5 shows that samples Nos. 1 through 6, 8 through 14 and 16 through 30 of Example 5 within the scope of the present invention, where ratio A/B of the minimum distance A between the periphery of the dummy layer and the side face of the protective section to the width B of the protective section in the section perpendicular to the direction of stacking was in a range from 0.01 to 0.08, showed failure rate of 2% or less after the continuous durability test, lower than those of comparative example (Nos. 7 and 15), thus proving excellent durability.

[0209]

Samples Nos. 1 through 6, 9 through 13, 16 and 18 through 30 of Example 5 where A/B was in a range from 0.02 to 0.07, in particular, showed failure rate of 1% or lower after the continuous durability test, thus proving excellent durability.

[0210]

Samples Nos. 1 through 6, 10 through 13, 16, 18 through 25 and 27 through 29 of Example 5 where A/B was in a range from 0.02 to 0.07, the dummy layer contained a metal, the internal electrodes were made of the same material as that of the dummy layer, thickness of the piezoelectric layer was 50 μm or more and the dummy layer contained 2% by weight or more of an inorganic composition, in particular, showed failure

rate of 0.8% or lower after the continuous durability test, thus proving even better durability.

[0211]

Sample No. 7 where ratio A/B was lower than 0.01 and sample No. 15 where ratio A/B was higher than 0.08, that were out of the scope of the present invention, showed 3% or worse failure rate after the durability test, thus proving durability lower than that of the present invention.

INDUSTRIAL APPLICABILITY

[0212]

The multi-layer piezoelectric element of the present invention can be applied to piezoelectric transducer. The multi-layer piezoelectric element of the present invention can also be applied to a multi-layer piezoelectric actuator used in an injection apparatus for injecting automobile fuel or ink of an ink jet printer, or a drive unit used in precision positioning device or vibration preventing device for an optical apparatus. The multi-layer piezoelectric element can also be used as a sensor element mounted in combustion pressure sensor, knocking sensor, acceleration sensor, load sensor, ultrasound sensor, pressure sensor, yaw rate sensor or the like, or used as a circuit component mounted in piezoelectric gyro, piezoelectric switch, piezoelectric transducer, piezoelectric breaker or the like.